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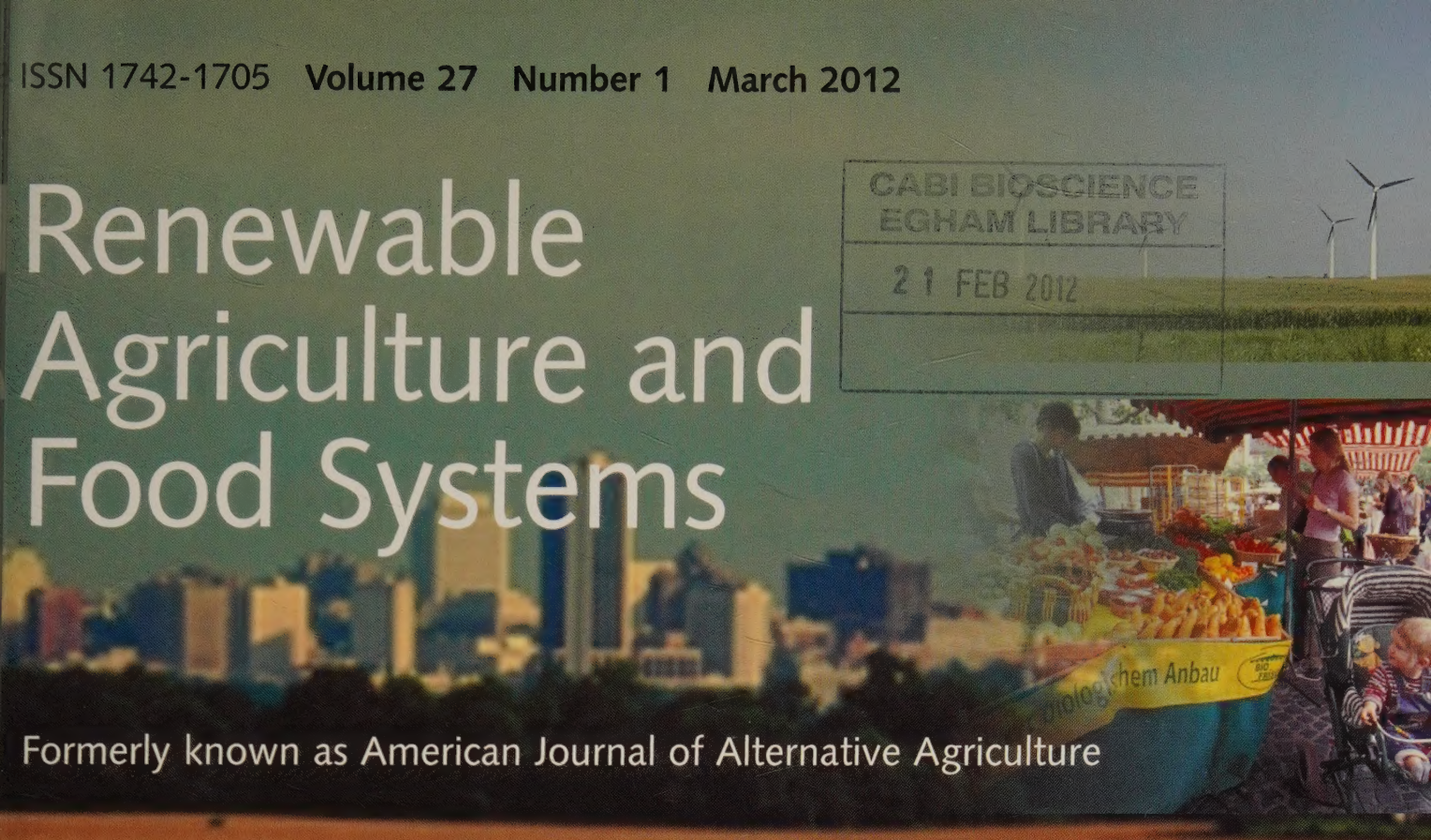

Special Issue

"Conservation Tillage Strategies in Organic Management Systems"
Special Guest Editors: Patrick M. Carr, Paul Mäder, Nancy G. Creamer, and John S. Beeby

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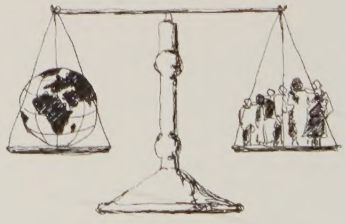

"Sustaining Earth and its People"

Scales image: Design, George Eisele, Lincoln, NE; artwork, Pat Scullion, ASA/CSSA/SSSA, Madison, WI, USA
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Introductory Editorial: Moving Forward

We are very pleased and excited to begin leading a talented, energetic and well-respected group of associate editors at *Renewable Agriculture and Food Systems*. We know that they will help us continue to publish a premier scientific journal focusing on the science underpinning an economically, ecologically and socially sustainable agriculture and food system. In addition, *Renewable Agriculture and Food Systems* relies upon the expertise and judgment of its reviewers to maintain the high standard of research it publishes. The names of the over 100 people who reviewed articles for the journal in 2011 can be found at: http://journals.cambridge.org/action/displayJournal?jid=RAF. We know that acting as a reviewer involves significant time and effort, and we very much appreciate their efforts. Without them, the quality of the journal could not be sustained.

We would like to take this opportunity to thank John Doran for his service to the journal over the past decade and more. As his final editorial demonstrated, he has a long and successful history with the journal and many accomplishments for which he can be proud. Thanks also to outgoing Associate Editors Molly Anderson (21 years of service for the journal), Mark Liebig (9 years, including Forum Editor) and John Ryan (9 years) for their service to the journal.

As incoming Editor-in-Chief, I wanted to tell you a bit about myself. I am a Professor of Sociology at Clarkson University in Potsdam, New York. I earned a PhD in Rural Sociology from Cornell University in 1995, an MS in Food and Resource Economics from the University of Florida in 1988, and a BA in Economics from The College of William & Mary in 1983. Previously, I was a policy analyst for the Henry A. Wallace Institute for Alternative Agriculture and the Director of the Sustainable Agriculture Research and Education (SARE) Program for the Southern Region. In addition, I have worked for the Foreign Agricultural Service on its food aid programs and served as a Peace Corps Volunteer in the Philippines.

The incoming Assistant Editor-in-Chief is Lydia Oberholtzer. She is a senior researcher with Penn State's Agricultural Economics and Rural Sociology department. She has worked on organic and small farm marketing issues for many years, and was previously with the Henry A. Wallace Institute for Alternative Agriculture. Her expertise is in local and organic food marketing and supply chains, food systems and access, small farm marketing (especially farmers' markets and CSA), as well as surveys and qualitative research.

To us, sustainable agriculture is not a regime of practices or regulations. It is a philosophy, a social movement and a set of economic, ecological and scientific principles simultaneously. In that vein, a sustainable agri-food system embodies several fundamental principles. These include biological complexity at the farm and landscape levels; diversity in the structure of production, processing and distribution systems; and reducing environmental impacts and protecting animal welfare at all stages of the food system. It also means the provision of safe, satisfying and nutritious food to all consumers, while providing sustaining livelihoods to farm and non-farm workers. The long view of history has shown convincingly that intensiveness and productivity is more resilient and effective when embedded within this type of social, economic and ecological framework. In addition, it has become clear that the global public will support, through policy and purchasing, this type of system. Therefore, one of our primary goals as incoming editors is to assist firms of all types, governments, non-governmental organizations, scientists and individuals around the world to transform their food systems toward sustainability as we have defined it.

Toward that end, we are excited about the current themed issue on conservation tillage and organic agriculture. As the guest editors indicate, the articles cover approaches to organic no-till agriculture in North America, and organic reduced till in conservation tillage in Europe. They conclude that,

> Multi-disciplinary teams of scientists and organic farmers are needed to solve the problems that are encountered when tillage is reduced or eliminated, and organic cash crops are grown. Our hope is that collaborations among those interested in this topic will be spurred as a result of this special issue, including trans-Atlantic efforts between European and North American researchers.

This dovetails with our vision of science as a vehicle for supporting an economically, ecologically and socially sustainable agriculture and food system. In addition, we have included in this issue an article on conservation agriculture in smallholder systems in Laos to highlight the importance of smallholder systems to contribute to a sustainable agriculture; but also to emphasize our commitment to a global reach for the journal.

Rick Welsh
Editor-in-Chief

Lydia Oberholtzer
Assistant Editor-in-Chief

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Editorial: Overview and comparison of conservation tillage practices and organic farming in Europe and North America

Tillage has been ubiquitous to crop production in most of the world for millennia. Implements used to till the soil that were pulled by animals are known to have existed at least as far back as 8000 BC.[1] However, growing concerns about the negative consequences of tillage on soil quality[2–4] spurred widespread interest in reducing tillage practices on farms, particularly in the Great Plains of North America where farming practices brought by immigrants from eastern regions and from Europe were not adapted because of the dry conditions that were encountered. This realization and other developments culminating in the Dust Bowl era during the 1930s made it obvious that innovative farming practices were needed to protect soil from erosion and degradation in quality. A logical consequence is modern no-till farming, where soil is disturbed minimally, if at all, when growing annual cash and forage crops. Advantages of no-till compared with clean or conventional tillage farming have been widely described in the scientific literature, with an excellent recent summary by Triplett and Dick[5].

Growth in modern no-till farming coincided with the development and commercial use of synthetic herbicides, notably first with 2,4-dichlorophenoxyacetic acid (2,4-D) in the USA[6], and paraquat in Europe[1]. Herbicides provided farmers with an effective alternative to tillage for controlling weeds but, unlike tillage, did not bury crop residue. The resultant vegetative mulch protected soil from water and wind erosion and, in semi-arid regions, reduced evaporation and improved soil-water storage efficiency[7]. The development of improved herbicides, along with seeding and harvesting equipment designed for use in no-till systems, resulted in the steady growth of this farming method, beginning in the 1990s[5].

Few herbicide options are available to organic farmers, in contrast to conventional farmers, forcing a continued reliance on tillage for weed control in systems managed organically. Research on alternative tillage methods for organic farmers is limited and has lagged behind comparable efforts directed at conventional farmers. Moreover, the so-called bio-herbicides such as natural vinegar, corn gluten and pine extracts that are permitted for use in certified organic farming in some regions of the globe are not, to date, allowed in Europe (European Council (EC) Regulation No. 834/2007 on organic production). Consequences of this dependence on tillage are the negative impacts on soil quality described elsewhere[2–4].

Arguments have been made about the inferiority of organic farming compared with conventional no-till farming in maintaining or enhancing soil quality[8], as well as providing other ecosystem services[9]. Curiously, comparisons of conventional no-till farming and tilled organic farming systems failed to reveal distinct soil quality advantages resulting from no-till farming methods. Rather, soil carbon and nitrogen levels were elevated under organic management in one study, presumably in part because of animal manure additions to the organic plots[10]. Potentially mineralizable nitrogen was over 20% higher in a tilled system transitioning to certified organic production, compared with conventional systems in the first few years of transitioning to long-term no-till management, in a separate study, probably because of the use of a pea green manure crop in the organic system[11].

There is interest in reducing tillage in organic farming systems for many of the same reasons that tillage has been reduced or eliminated in conventional farming. Peigné et al.[12] point out that conservation tillage practices, where at least 30% of the soil surface is covered by a dead vegetative mulch after seeding, could reduce fuel use, enhance soil microbial activity and increase water infiltration rates, as well as reduce soil erosion and leaching of plant nutrients if adopted by organic farmers. The researchers acknowledge the weed control challenges when considering a transition from clean tillage to conservation tillage systems, noting that changes in weed dynamics often deter adoption of conservation tillage by organic farmers in Europe. Likewise, concern over an inability to control weeds when tillage is reduced is a major impediment to adoption of conservation tillage practices among organic farmers in the USA (Duane Boehm, pers. comm.).

Different strategies have been considered for adapting conservation tillage practices to organic farming systems. In North America, most of the present research is directed at reliance on vegetative mulch created by killed cover crops to suppress weeds during a subsequent cash crop phase within a longer crop rotation[13]. This idea is not new and apparently originates from the use of drums with attached blunt blades to kill cover crops in conventional no-till farming systems in Brazil[14,15]. The effectiveness of using a blade roller[13], also referred to as a roller–crimper[16], in killing winter rye (*Secale cereale* L.), winter wheat (*Triticum aestivum* L.) and black oat (*Avena strigosa* Schreb.) in the southern USA was reported by Ashford and Reeves almost a decade ago[17]. The two researchers concluded that the three cover crops could be killed effectively if blade rolling was delayed until at least

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the early milk growth stage (BBCH growth stage 73)[18] of kernel development. Subsequent research confirmed this observation for winter rye in the mid-Atlantic region of the USA[16].

Creamer et al.[19] compared termination of several cover crop species using a sickle bar mower, flail mower and roller attached to a blade plow in the US Midwest region during the early 1990s. The researchers concluded that while there could be problems with clogging when terminating vine-like cover crops [e.g., hairy vetch (*Vicia villosa* Roth)], sickle bar mowing was as effective as the roller/blade plow in killing cover crops, and left a thick vegetative mulch that suppressed weeds. Creamer and Dabney[20] indicated that problems could be encountered when attempting to kill cover crops by rolling, as well as with other mechanical methods that exclude tillage, including several identified by others[21].

Improvements in blade roller design have occurred since early research was conducted. Newer designs have proven effective in terminating cover crops, and have enhanced the comfort of those operating blade rollers in the field[14,15]. Reports on the ability of cover crop residue to provide near season-long weed control when killed by modern blade rollers exist, and considerable enthusiasm has been generated for 'no-till' organic farming where tillage is eliminated entirely during certain crop phases of a crop rotation[22]. Six papers included in this special issue describe efforts to develop organic conservation tillage practices in North America, and the use of cover crops and blade rollers is a prominent, if not exclusive, focus of the research that is described.

Mirsky et al.[23] discuss efforts to develop organic conservation tillage systems in the mid-Atlantic region, where much of the recent published research on blade rollers and cover crops in the context of organic no-till has been conducted in North America[16,24]. The authors note that an inability to suppress weeds consistently is a major obstacle that must be overcome for rolled and killed cover crop residue to be considered a viable weed control tool in organic farming systems. Reberg-Horton et al.[25] indicate that growing conditions in the southeast region of the USA allows for prolific growth by cover crops, sometimes exceeding 9000 kg ha^{-1} of dry matter, which results in a thick vegetative mulch capable of suppressing weeds in many cash crops. The southern researchers acknowledge that additional weed control measures sometimes are needed if cover crop mulch alone is relied on for season-long weed control.

Delate and Cwach[26] in the US Midwest region and Luna et al.[27] in the US Pacific Northwest region consider the efficacy of rolled and killed cover crop mulch for weed control in tomato (*Lycopersicon esculentum* Mill.) and several other crops. Delate and Cwach[26] report that excellent early-season weed control can be provided by cover crop mulch, but acknowledge that suppression of weeds may be diminished by mid-season. Luna et al.[27] recognize the potential that organic no-till has in eastern portions of North America, but consider lack of weed control as only one of several problems which prevents this cropping strategy from being adopted in the Pacific Northwest region presently. Carr et al.[28] report that annual weed growth can be suppressed by rolled and killed cover crops in the semi-arid northern Great Plains region of the USA, but suggest that cover crop mulch will be ineffective in controlling established perennial weed species such as Canada thistle (*Cirsium arvense* [L.] Scop.). Shirtliffe and Johnson[29] indicate that weed growth can be greater when cover crops are killed by disking compared with mowing and blade rolling, but acknowledge that refinement is needed before organic no-till is a viable production system on commercial organic farms in western Canada.

A recurring theme from recently completed and ongoing research on organic no-till farming in North America is that efficacy must be improved when relying on killed cover crop mulch for weed control in subsequent crops[23–28]. Interest in organic farming systems which rely on rolled and killed cover crop residue for weed control also has been expressed by European scientists[12]. This is documented, for instance, by a paper presented at the 16th IFOAM Congress in Italy on the direct seeding of fababean (*Vicia faba* L.)[30]. Although a recent review of the literature failed to identify published results from European field studies on use of killed cover crop mulch for weed suppression[12], seeding fababean directly into small-grain stubble without pre-plant tillage has been considered by German scientists at the University of Bonn[31].

Efforts to reduce tillage in organic farming systems by European scientists generally are not focused on its complete elimination, as is the case in North America. Instead, European researchers are working mainly on methods that decrease the amount of inversion tillage being used by organic farmers, particularly when a pasture ley is included in rotations with annual cash crops. This emphasis on reducing, rather than eliminating, tillage completely is exemplified in a series of papers summarizing results from the first 6 years of a long-term field study at the Research Institute of Organic Agriculture located at Frick, Switzerland[32–35]. The experiment, established in 2002, compared two tillage systems across a winter wheat (2002–2003)–sunflower (*Helianthus annuus* L.; 2004)–spelt (*T. spelta* L.; 2005)–grass/clover polyculture (2006–2007)–maize (*Zea mays* L.; 2008) crop sequence between 2002 and 2008: a clean or conventional tillage system where primary tillage was done using a moldboard plow and a reduced tillage system where primary tillage was accomplished using a chisel plow. A stubble cleaner or skim plow was used for removal of the grass–clover ley before maize in both tillage systems, with secondary tillage accomplished using a rotary harrow.

Reduced nitrogen mineralization in spring and elevated weed competition under reduced tillage probably explains the mixed crop yield results between 2002 and 2005, when

small-grain crop yields were depressed, while oilseed crop yield was elevated slightly[32,33]. Forage yield of the grass-clover ley was 25% higher in reduced tillage plots during 2006–2007 because of improved water retention[34], and maize silage yields were 34% higher under reduced tillage in 2008, despite weed populations that were two to five times higher than in conventional tillage plots[34]. Greater enhancements in soil quality were detected under reduced tillage compared with conventional tillage during the first 6 years of this study and are summarized by Gadermaier et al.[35] in this special issue.

Colonization of maize roots by arbuscular mycorrhizae across tillage systems was considered by the Swiss researchers in 2005. Interestingly, no enhancement in maize root colonization was detected in reduced tillage compared with conventional tillage plots[32]. Rather, arbuscular mycorrhizal infection of maize roots was slightly higher under conventional tillage. These results contrast with those of others[36] who found root colonization by arbuscular mycorrhizae to be higher under reduced tillage compared with conventional tillage. Kabir[37] concluded in his review of the literature that tillage generally is harmful to arbuscular mycorrhizae and the hyphae networks that are formed. However, the impact of tillage on arbuscular mycorrhizae can be confounded by such things as timing of field activities[36,37] and the fungal species that are present[38]. This was illustrated even at the intra-specific level of the mycorrhizal fungus *Glomus intraradices*, where the diversity of mitochondrial large subunit rDNA haplotypes was found to be higher under reduced tillage compared to conventional tillage in the Frick study[39].

The negative effect that tillage can have on arbuscular mycorrhizal populations and other edaphic factors led some researchers to suggest that adoption of reduced tillage practices fails to capture the soil quality improvements and other benefits that only result when tillage is eliminated completely from farming systems. Grandy et al.[40] argued that no-till practices must be continuous throughout a crop rotation; many soil quality improvements can be undone in long-term no-till fields by a single tillage operation. Kettler et al.[41] reported that soil quality declined at shallow soil depths (0–7.5 cm) following the single use of a moldboard plow in long-term no-till plots, while soil quality improved at a 7.5–15 cm soil depth, concluding that occasional tillage may result in stratification rather than an overall decline in soil quality. Continuous no-till farming, like that described by Grandy et al.[40], has not been accomplished successfully when farming organically on a commercial scale[42]. Still, several soil quality and other potential advantages have been attributed to organic no-till farming as it presently is described[43], and explains the motivation for many of the studies on organic no-till in North America[23,25–29]. European researchers are no less motivated than their North American colleagues in developing viable conservation tillage practices for adoption by organic farmers, but their approach is different and focused on reducing, but not eliminating, tillage when farming organically.

The papers included in this special issue are intended to provide readers with an overview of recently completed and ongoing efforts by North American scientists to develop viable organic no-till systems, and by their European counterparts to develop farming systems that require less tillage when growing organic cash crops. Benefits from adopting reduced tillage and no-till methods for farming organically are identified, as are obstacles that must be overcome before these practices are adopted by large numbers of organic farmers. Multidisciplinary teams of scientists and organic farmers are needed to solve the problems that are encountered when tillage is reduced or eliminated, and organic cash crops are grown. Our hope is that collaborations among those interested in this topic will be spurred as a result of this special issue, including trans-Atlantic efforts between European and North American researchers.

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Development of reduced tillage systems in organic farming in Europe

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Abstract

No-tillage and reduced tillage are considered sustainable options of conservation tillage. While US organic farming researchers have focused on no-tillage, European organic farming researchers have concentrated on reduced tillage through the reduction of tillage depth or the application of noninversion tillage practices. Combinations of these two approaches have been implemented by the use of the two-layer plow or the layer cultivator. These innovations often came from farmers, aiming at reducing off-farm inputs such as fuel, and saving costs and labor, while at the same time building up soil fertility. Systematic, documented research on reduced tillage systems in Europe started only 1–2 decades ago, with experiments in Germany, Switzerland and France. While most experiments mimic stockless farms, other experiments include fodder crops such as grass–clover ley and applications of manure and slurry as is typical for mixed farms with animals and crops. Soil organic carbon, microbial activity and soil structure are often improved in the upper soil layer under reduced tillage compared with plowed soils. However, these positive findings were confounded by lower yields in some cases and enhanced weed pressure, except for the two-layer plow. Often it was not possible to determine whether and to what extent yield reduction was due to weed competition or to nitrogen shortage, because of retarded nitrogen mineralization in spring in reduced tillage systems. In systems with manure use, also higher soil fertility measures concomitant with increased yields were reported under reduced tillage. Indeed, it is difficult to gain an overview on research activities dealing with reduced tillage in organic farming in Europe due to dispersed experimental infrastructures and the scarcity of peer-reviewed published literature. To close this knowledge gap a European Network is being established aiming at further developing reduced tillage systems in organic farming, addressing the issue of carbon sequestration and N_2O emissions, as well as weed and nutrient management.

Key words: reduced tillage, no-tillage, conservation tillage, organic farming, Europe

Introduction

The loss of large areas of arable land by erosion calls for more sustainable cropping systems[1–3]. Both organic farming and no-tillage offer many benefits in view of soil fertility and biodiversity[4–6]. No-tillage systems were developed under conventional management aiming at conserving soil moisture, protecting soils from erosion and minimizing soil compaction. The combination of organic farming and no-tillage may provide additional benefits to the environment and further improve the resource use efficiency[7]. However, in no-till systems, weeds are usually controlled by herbicides, and plants fertilized via mineral nitrogen, methods that are not permitted in organic farming systems.

Only relatively small areas are currently under no-tillage in Europe as compared to USA, Brazil, Argentina, Canada and Australia[8,9]. Both organic farming and no-tillage have been identified as promising options to sequester carbon in European soils[10]. However, only a few studies so far have analyzed carbon pools across the whole soil profile. While organic carbon, in most cases, was elevated under no-tillage in upper soil layers, it may decrease in deeper soil layers, in particular when organic matter input to the systems is low[11]. Climate-change mitigation potential of no-tillage systems may also be offset by elevated N_2O emissions, which are fostered under the more anaerobic conditions prevailing in this system[12,13]. Recent research indicates that integrating appropriate conservation agriculture approaches into organic cropping systems may overcome these limitations. For example, N_2O emissions were greater when microbial soil populations were exposed to low C/N ratios by the use of mineral N-fertilizers in conservation

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agriculture[13,14]. This may be of lesser importance when using organic fertilizers. Notwithstanding, the introduction of conservation tillage practices such as no-tillage or reduced tillage can further improve organic systems with respect to soil fertility. While no-tillage system development in organic farming is mainly restricted to the USA[15], farmers and researchers in Europe focus on reduced tillage systems. The current article gives an overview on the development of reduced tillage in organic farming in Europe and identifies relevant research gaps.

Reduced Tillage Systems in Europe

The idea of noninversion soil preparation in organic farming dates back to the early 1950s, when Rusch[16] developed his ideas of organic farming. His vision was to mimic a stable, natural ecosystem, and pointed out that each soil layer has its adapted biocenosis, which should not be disturbed by deep inversion plowing. In practice, the 'credo' of organic farmers in these times was 'shallow plowing and deep loosening' [Otto Schmid, organic farming advisor at FiBL (the Research Institute of Organic Agriculture), pers. comm.]. Nowadays, reduced tillage practices in organic farming comprise several practices such as the reduction of plowing depth but also noninverting, less-invasive soil loosening, e.g. by the chisel plow[17]. Carter[18] pointed out that conservation tillage practices in humid temperate regions need adaptation to soil and climatic conditions. This applies in particular to organic farming systems, because no synthetic nitrogen fertilizers and herbicides are available.

Rationale for the Reduced Tillage Approach in Organic Farming in Europe

No-tillage started in the USA triggered by tragic dust storms in the mid-western USA in the 1930s. This served as a wake-up call to how human interventions in excessive soil cultivation led to unsustainable agricultural systems[19]. Later on in the 1980s and 1990s no-till was introduced in Brazil and moved to Argentina. Currently approximately 26 million hectares are under no-till in Brazil and approximately 20 million hectares in Argentina[8,9].

We interpret the different approaches in Europe (reduced tillage) and USA (no-tillage) in organic farming in the context of the predominant pedo-climatic conditions of the two continents and the type of farms. European farmers in large areas are faced with humid and cold conditions during crop growth, limiting the suitability of no-tillage practices. Mixed farms with animals, fodder and cash crops are considered ideal in view of nutrient recycling, environment protection and specifically the farms' influence on climate change in Europe.

In this context, there are a number of arguments for a better suitability of reduced tillage under humid temperate climate, such as manure incorporation, faster warming up of soil in spring, resulting in faster nitrogen mineralization, better control measures of perennial weeds and removal of grass–clover by shallow undercutting of the whole field. Moreover, in crop rotations comprising maize and wheat, a shallow incorporation of straw residues into the soil may result in faster decay, and thus in a better regulation of pathogens such as *Fusarium* sp. Altogether, reduced tillage may also lead to faster crop establishment able to better compete with weeds compared with no-tillage systems. Nonetheless, newly developed systems such as the 'roller/crimper' system attracted European researchers, who recognize the need for inclusion of more conservation techniques such as the systematic use of cover crops[17,19,20].

Machinery, Equipment and Research Activities

Organic pioneers, aiming at materializing the ideas of reduced soil tillage, developed special equipment, such as the Kemink system[21], the ridge tillage system of Turiel[22], the two-layer plow and the layer cultivator. The two-layer plow inverts the soil in the upper soil layer and loosens deeper layers. Similarly, the layer cultivator mixes the soil in the upper soil layer and also loosens deeper layers. More recently, machines were created allowing for a shallow cleaning of stubbles or the removal of grass–clover such as the stubble cleaner (German: Stoppelhobel, Zobel—Stahlbau, Germany, a type of skim plow, undercutting the whole field) or the Ecomat™ (Kverneland, Germany), which allows for quite shallow plowing.

Despite some early attempts to introduce reduced tillage in organic farm operations, systematic research under organic farming conditions started relatively late. Experiments established since the mid 1990s often included not only two-layer systems such as the layer plow and the layer cultivator, but systems with variable tillage depths were also tested. There is no general agreement on what to call a reduced tillage system. Here, we define all tillage systems as reduced that operate at shallower depths or at lower intensity compared to customary plowing in a given region. To date many research findings are only available in 'grey' literature such as conference proceedings and reports, with restricted availability. A most useful overview on organic farming without deep plowing was recently published in German by Schmidt[23]. Table 1 gives an overview on some key experiments on reduced tillage in organic farming in Europe.

In almost all these experiments reduced tillage enhanced soil organic carbon contents, soil microbial activity and soil structure in the upper soil layer. In general, greatest differences were observed when comparing conventional plow treatments (full inversion to 30 cm)

Table 1. Research experiments with reduced tillage under organic conditions in Europe (selection).

Experiment start, end year	Country	Tillage systems	Research activities
Rommersheim[24–26] Stiftung Ökologie und Landbau 1995–2004	Germany	Plow (30 cm) Two-layer plow (30 cm) Layer cultivator (30 cm)	Soil organic carbon Soil microbiology Soil fauna Soil physics Yield Root length Weeds
Scheyern[27] organic 1995 (ongoing)	Germany	First factor: farming system Second factor: plow (30 cm approx.) Plow (18 cm) Rotary hoe, cultivator (18 cm max.) Third factor: fertilization	Soil organic carbon Soil microbiology Yield N_2O emission
Gladbacherhof[28,29] 1998 (ongoing)	Germany	First factor: plow (30 cm) Two-layer plow (30 cm) Plow 15 cm (till 2003) or Cultivator (15 cm) (since 2004) Layer cultivator (30 cm) Second factor: crop rotation	Soil organic carbon Soil microbiology Soil nutrients Soil physics Yield Weeds
Kleinhohenheim[30–32] 1998 (ongoing)	Germany	First factor: plow (25 cm) Two-layer plow (25 cm) Plow (15 cm) Chisel (15 cm) Second factor: stubble tillage	Weeds
Tillage trial Lyon[33,34] 1999 (ongoing)	France	Plow (30 cm) Plow (15 cm) Chisel plow (15 cm) Rotary cultivator (6 cm)	Soil organic carbon Soil microbiology Soil structure Earthworms
Tillage trial Frick[7,35–38] 2002 (ongoing)	Switzerland	Plow (15 cm) Chisel plow (15 cm) plus stubble cleaner (5 cm)	Soil organic carbon Soil microbiology Earthworms Intra-specific diversity mycorrhiza Yield Weeds
Staatsdomäne Frankenhausen[22,39,40] Lindenbreite 2002 (ongoing)	Germany	Plow (25 cm) Ecomat (7 cm) Ridge till (Turiel)	Soil microbiology Earthworms Soil physics
Borovce[41] Started in 2006	Slovak Republic	Plow (20 cm) Chisel plow (15 cm)	Soil organic carbon Soil microbiology Earthworms pH

with layer cultivation. Benefits of two-layer plowing compared with conventional plowing were less pronounced.

Yields were often similar in plow systems and systems using a two-layer plow, but were lower in systems using a two-layer cultivator or chisel. Unexpectedly, the chisel plow combined with a stubble cleaner, in the tillage trial Frick (Table 1), resulted in even higher yields as compared to the plow system in the long term. This was attributed to the relatively high stocking density mimicked in this experiment, allowing for better timing of available nitrogen to the crops according to their needs, and the inclusion of green manures in the rotation. Moreover, the 2-year grass–clover ley contributed to weed suppression. This experiment clearly demonstrated that tillage systems need the specific adaptation of system components such as tillage timing, the planting of green manures and the use of new equipment to optimize a system.

Weed pressure was generally acceptable in two-layer plow systems, but was increased in two-layer cultivator

systems and systems with a chisel plow. In particular monocotyledonous weeds were enhanced in reduced tillage systems.

Research Challenges

The results of reduced tillage experiments in organic farming obtained so far clearly demonstrate the superiority of these systems to conventional plow systems with respect to soil biology and soil fertility. However, there are major challenges and research gaps inhibiting more widespread application of reduced tillage in organic systems in Europe. Moreover, the experiments are extremely scattered and often published in national languages only. To close these research gaps, a European Network[42] is currently being established to address the following issues:

- The lack of knowledge on the effect of reduced tillage and no-tillage systems under organic farming on the soil carbon stock across the whole soil profile. This information is urgently needed to assess these systems' potential to mitigate climate change.
- Because N_2O emissions are strongly dependent on available carbon and nitrogen, as well as on soil temperature and soil oxygen, climate gas-emission studies should be performed in various tillage systems and pedo-climatic zones.
- The higher weed pressure, with perennial weeds in particular, under reduced tillage calls for smart technological and biological solutions for efficient weed control. The acceptability of 'bio-herbicides' such as vinegar and bio-control organisms should be discussed anew.
- The optimum integration of green manure systems shall be investigated to guarantee the crops' nitrogen needs.

We expect that this Network will also facilitate the exchange of information between European and American researchers in the field of conservation tillage techniques.

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Organic zero-till in the northern US Great Plains Region: Opportunities and obstacles

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Abstract

The use of killed cover crop mulch for weed suppression, soil erosion prevention and many other soil and crop benefits has been demonstrated in organic no-till or zero-till farming systems in eastern US regions and in Canada. Implements have been developed to make this system possible by terminating cover crops mechanically with little, if any, soil disturbance. Ongoing research in the US northern Great Plains is being conducted to identify cover crop species and termination methods for use in organic zero-till (OZ) systems that are adapted to the crop rotations and climate of this semi-arid region. Current termination strategies must be improved so that cover crop species are killed consistently and early enough in the growing season so that subsequent cash crops can be grown and harvested successfully. Delaying termination until advanced growth stages improves killing efficacy of cover crops and may provide weed-suppressive mulch for the remainder of the growing season, allowing no-till spring seeding of cash crops during the next growing season. Excessive water use by cover crops, inability of legume cover crops to supply adequate amounts of N for subsequent cash crops and failure of cover crops to suppress perennial weeds are additional obstacles that must be overcome before the use of killed cover crop mulch can be promoted as a weed control alternative to tillage in the US northern Great Plains. Use of vegetative mulch produced by killed cover crops will not be a panacea for the weed control challenges faced by organic growers, but rather one tool along with crop rotation, novel grazing strategies, the judicious use of high-residue cultivation equipment, such as the blade plow, and the use of approved herbicides with systemic activity in some instances, to provide organic farmers with new opportunities to incorporate OZ practices into their cropping systems. Emerging crop rotation designs for organic no-till systems may provide for more efficient use of nutrient and water resources, opportunities for livestock grazing before, during or after cash crop phases and improved integrated weed management strategies on organic farms.

Key words: organic farming, ecological farming, conservation tillage, no-till, roller-crimper, cover crops, crop rotation

Introduction

Conservation tillage encompasses those practices that maintain at least 30% of previous crop residue on the soil surface following harvest through seeding of a subsequent crop[1], and includes no-till or zero-till where soil is undisturbed by tillage from seeding through harvest[2]. Much of the recent published literature on conservation tillage in the context of organic farming was generated from studies in the eastern US or in Canada within North America, and is referenced in other papers in this special issue[3,4]. Research in the US northern Great Plains on organic farming methods and conservation tillage began as separate research venues in the 20th century. Recognizing the strengths that both systems have to offer in this region, several studies on the potential of organic zero-till (OZ) are under way or

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recently have been completed. The objective of this paper is to provide the context for a discussion on OZ research efforts by reviewing the importance of climate, cropping system development, conservation tillage, cover crops and organic farming in shaping crop production efforts in the region. This will be followed with a brief summary of OZ research efforts in Montana, North Dakota and South Dakota.

Climate and Traditional Cropping Practices in the Northern Great Plains

The US northern Great Plains comprise a vast, agriculturally important region consisting of North Dakota, most of South Dakota and Montana, and northeast portions of Wyoming and northwest Nebraska. The region is characterized by long, cold winters and short, warm summers, along with erratic precipitation[5]. Precipitation typically is limited, ranging from roughly 300 to 500 mm annually, with declining amounts generally occurring from east to west. Prolonged dry periods accompanied with strong winds are common during summer months[5]. Highly variable precipitation, along with seasonal and diurnal fluctuations in temperature, is a serious climatic challenge faced by farmers in the region. However, the unpredictability of the limited precipitation that is received poses the greatest impediment to sustained crop production.

Hard red spring wheat (*Triticum aestivum* L. emend Thell.) has been the dominant grain crop grown in much of the region, largely because of its drought-evasive or -resistant traits[5]. Spring wheat was grown in alternate years, with a long, 20- to 21-month fallow period between successive crops, throughout most of the 20th century[6]. Precipitation was stored in the soil during the fallow phase to mitigate the negative impacts of drought in the wheat–fallow system[6]. The fallow period also allowed accumulation of plant-available nitrogen (N) from organic matter mineralization, and provided weed control opportunities[7]. Tillage was the primary and, oftentimes, only tool used to kill weeds and stimulate organic matter breakdown by incorporating crop residue into soil.

The wheat–fallow system was a major contributor to severe soil erosion problems that plagued the northern Great Plains during much of the 20th century. Loss of soil organic matter was also an important problem with the wheat–fallow system. Bauer and Black[8], as well as others[9], reported declines in organic matter content of up to 60% within 40 years of adopting wheat–fallow compared with native prairie. Natural soil fertility, water-holding capacity and many other soil properties favoring sustained crop production were diminished considerably using the wheat–fallow system compared with uncultivated soil.

The Growth of Conservation Tillage and Intensification of Cropping Systems

The introduction of synthetic herbicides, beginning with 2,4-dichlorophenoxyacetic acid (2,4-D) in the late 1940s, was a boon to those concerned about the deleterious effects of tillage on the soil during the fallow period. Heavy reliance on tillage no longer was necessary for weed control, particularly as more effective herbicides were developed. By the mid-1990s, herbicides had effectively replaced tillage used for weed control in many farming operations across the US Great Plains[10]. Tillage also became unnecessary for seedbed preparation as planting equipment was developed which enabled farmers to establish crops in fields where crop residue was maintained on the soil surface[2].

An important purpose for the long fallow period was to recharge soil water for a subsequent wheat crop, but the transition to conservation tillage resulted in enhanced soil-water storage because of improvements in soil quality[11,12]. Water conservation was greatest under no-till[12] and explains the interest in this form of conservation tillage in the US northern Great Plains. As a result, conservation tillage methods, particularly no-till, allowed cropping systems in this semi-arid region to intensify. That is, the long fallow period occurred less frequently between successive crops, or it was eliminated entirely between annual crop phases. This intensification in cropping systems also coincided with growing concerns about the economic efficiency of the wheat–fallow system[13,14]. By the late 20th century, the amount of cropland that was fallowed declined throughout the US northern Great Plains[15].

Cropping system intensification necessitated diversifying wheat-based cropping systems to avoid the build-up of certain pests[16], and to optimize conversion of plant-available water to wheat grain[17]. Research in Montana and North Dakota documented the positive impact of growing legumes, such as field pea (*Pisum sativum* L.) and chickpea (*Cicer arietinum* L.), as well as other broadleaf crops, such as flax (*Linum usitassimum* L.), on subsequent wheat performance compared with annual wheat monoculture[17–19]. The positive rotation effect was attributed to disease suppression, soil-water recharge and biological N-fixation benefits in the case of legumes.

Cover Crops in Conventional Cropping Systems in the US Northern Great Plains

The benefits that cover crops can provide when incorporated into diversified cropping systems are well documented. Cover crops typically are grown to protect the soil from surface erosion, as well as to provide other benefits including soil improvement, disease suppression and to reduce N-leaching below the root zone[20]. Teasdale[21] focused on the role that cover crops have in weed management in his review of the literature, while Cherr et al.[22] discussed the use of cover crops as soil-amending green manures. The OZ systems developed in the eastern USA have been very reliant on winter annual cover crops[3].

Organic farmers have used legume cover crops as green manures in place of a cash crop during selective phases of crop rotations in the US northern Great Plains. In contrast,

conventional farmers typically have not included cover crops in rotations, although research focused on the use of green manures to replace fallow (also known as green-fallow) was conducted during the 1990s. With the decline in fallow and the intensification of cropping systems in the northern Great Plains, there are few opportunities for growing green-fallow cover crops in conventional cropping systems at present.

Snapp et al.[20] included in their review of the literature a discussion on the cover crop choices that are available to farmers, including a listing of the advantages and disadvantages of various crop species as well as groups (i.e., small-grain crops) when grown for this purpose. The authors noted research[23] demonstrating the positive impact that a sweetclover (*Melilotus officinalis* L.) cover crop can have on subsequent wheat crop performance in the northern Great Plains. Other research[24] demonstrated the positive rotation benefit of preceding wheat with sweetclover in this region. In contrast, wheat yield depression can result occasionally after a sweetclover cover crop[25], presumably because of soil moisture shortages following the biennial legume, which can be a relatively heavy water user in some environments[26–28]. The yield depression that can result following sweetclover is most evident when termination is delayed until later in the sweetclover growing season[28]. These studies support the observation by Snapp et al.[20] that complex water relations govern successful incorporation of sweetclover and other cover crops in rotations with wheat and other cash crops in the northern Great Plains.

Townley-Smith et al.[29] echoed the concern of others[30] in the US northern Great Plains that legume cover crops, when green manured, were capable of depleting stored soil water to such an extent that grain yield of subsequent crops could be depressed. Of several legume species that were considered for cover crop use in the region, field pea was identified as the most promising[29]. Field pea produced more cover crop dry matter than four other legume species [first-year alfalfa (*Medicago sativa* L.), fababean (*Vicia faba* L.), lentil (*Lens culinaris* Medik.) and Tangier flatpea (*Lathyrus tingitanus* L.)] and, along with fababean, fixed more N biologically than the other legume species in the seeding year. Likewise, other studies[26,31] identified field pea and fababean as being a superior choice for a green manure and cover crop compared with other annual legumes in the northern Great Plains.

Several species have been evaluated as potential cover crops in the US northern Great Plains. Power[27] concluded that fababean and field pea were the best cover crop replacements for fallow in a wheat–fallow system of the 10 legume species that were considered, including sweetclover. This researcher noted that the two pulse crops produced more above-ground biomass than other cover crop species when seeded in early May and harvested in late June, averaging from 1550 kg (fababean) to 3940 kg (field pea) of dry matter per hectare. Total N accumulation in above-ground biomass was also greater for fababean and field pea than other legume cover crops when terminated in June. These two legume species, along with lentil, are superior biological N-fixers compared with most other annual pulse crops grown in the northern Great Plains[31].

Tangier flatpea and field pea were considered as cover crop replacements for fallow in rotation with wheat in a 4-year study in central North Dakota[30]. The researchers concluded that both species produced sufficient dry matter to protect the soil surface from erosion when terminated at or before flowering, and that wheat grain yield following legume cover crops was not depressed compared with the fallow control. Delaying cover crop termination until pod formation or later sometimes reduced subsequent wheat grain yield because of insufficient recharge of soil water prior to planting the wheat crop. Similarly, wheat yield following a lentil cover crop was depressed by 25% compared with the fallow control when cover crop termination was delayed until full bloom or more advanced growth stages[32]. However, Pikul et al.[32] concluded that a lack of available N following the legume cover crop explained the negative rotation effect on wheat grain yield rather than a depletion of stored soil water. Studies conducted by other researchers[33] in the northern Great Plains support the contention that N deficiencies, rather than stored soil-water deficits, can explain grain depression when wheat follows legume crop species in some low-N environments when no supplemental N is provided. These studies[32,33] demonstrate that biological N-fixation by legume cover crops may be insufficient to supply N needs of subsequent cash crops under some conditions in the US northern Great Plains.

Organic Farming Research in the US Northern Great Plains

Research on organic farming methods in the US northern Great Plains was initiated in the mid- to late 1980s after the widespread adoption of synthetic fertilizers and pesticides. Small-grain cultivar studies were completed under organic management[34–36]. More recently, Stofferahn[37] summarized the environmental–ethical and other factors that explained the motivation of North Dakota farmers to grow crops organically. However, results of these research efforts fail to provide insight on OZ methods being considered for adoption in the region.

Recognition of the soil quality benefits that result when conservation tillage practices are adopted by conventional farmers who rely on synthetic herbicides for weed control has resulted in criticism directed at the frequent use of tillage in organic systems[38]. However, potentially mineralizable N was higher in a pea–wheat–lentil–barley (*Hordeum vulgare* L.) cropping system transitioning to certified organic management compared with various cropping systems transitioning to conventional zero-till management in Montana[39]. The 4-year organic rotation included a winter pea cover crop that was green manured prior to seeding winter wheat, whereas cover crops were

not included in the conventional zero-till systems. Miller et al.[39] established the cover crop phase by sowing pea seed in the fall directly into barley stubble without any pre-plant tillage, and avoided tillage after wheat, lentil or barley grain was harvested, unless absolutely necessary, to control weeds in the organic system.

Grain yield of winter wheat following winter pea cover crop in an organic system was equal or superior to wheat yield levels in a conventional zero-till system that was diversified, did not include cover crops and received up to 157 kg ha^{-1} of fertilizer N[39], depending on the year. The relatively high grain yields in the organic system were attributed to slower wheat growth and, conversely, more efficient uptake and conversion of soil-stored water by plants in organic plots as the growing season progressed. However, soil nitrate-N, phosphorus (P) and potassium (K) content were lower under organic management. These results demonstrated that legume cover crops may not be sufficient to supply the N needs of many cash crops in the US northern Great Plains, leading Miller et al.[39] to suggest that manure from livestock might be needed on organic farms to maintain soil fertility at a level that supports sustained crop production over the long term. Entz et al.[40] reported that soil nitrate-N, along with K and sulfur (S) levels, generally were sufficient on 14 organic farms, including one in North Dakota. However, the Canadian researchers noted that soil P levels were deficient for sustained crop yields on a majority of the farms. Russelle et al.[41], as well as Krall and Schuman[42], argued that livestock offer many ecosystem services when integrated into cropping systems on farms, including soil fertility improvements.

Liebig and Doran[43] found that organic carbon (C) and total N levels tended to be elevated in organic fields compared with conventional fields where some tillage is used in the US northern Great Plains. These two scientists speculated that the higher organic C and total N levels in fields farmed organically may have been '... due to less frequent tillage and inclusion of cover crops in the crop sequence [on the organic farm].' The surprising observation that tillage was more common under conventional management was explained by the inclusion of forages (e.g., alfalfa) in crop rotations on the organic farm, and the absence of forages in crop rotations on the conventional farms. These results suggest that increasing crop rotation diversity, using forage and cover crops, and reducing tillage in organic systems is an important goal for improving soil quality in organic cropping systems in the northern Great Plains.

Thirty-two farmers, roughly half of whom were farming organically, were surveyed about their farming practices and contrasted with conventional farming practices that were used in the late 1980s in South Dakota[44]. Results of the survey and follow-up interviews revealed that the 32 farmers used more diverse crop rotations, which oftentimes included cover crops used as green manures, compared with conventional farmers. Sweetclover and, to a lesser extent, 'forage sudan' [i.e., presumably sudangrass, *Sorghum sudanense* (Piper) Stapf.], were the most common cover crop species, grown at the time as an alternative to traditional fallow. Although conventional farmers on panels questioned the use of such 'low value' crops in cropping systems, organic and other non-conventional farmers felt that soil fertility and pest control benefits provided by cover crops and crop rotation diversity offset any immediate economic concerns when they were grown.

Menalled et al.[45] considered the transition from conventional to organic farming management in the northern Great Plains. The researchers acknowledged the importance of legume cover crops grown as green manures as a source of N when followed by cash crops in rotations. Use of cover crops and vegetative mulches for weed suppression also was noted as a way to prevent sunlight from reaching weeds and weed seeds on the soil surface and, in some instances, as sources of allelopathic substances. No mention was made of OZ in the publication, although Menalled et al.[45] did caution readers to be careful when relying on tillage for weed control as it can lead to increased risk of soil erosion.

Organic Zero-till Research in the Northern Great Plains

Much of the recent published literature on conservation tillage in the context of organic farming was generated from studies in the eastern USA or in Canada within North America, and is referenced in other papers in this special issue[3,4,46]. Results of recent studies on the use of cover crops in organic management systems within the US northern Great Plains have been published[39,47,48], but none of this research considered the use of cover crops in an OZ system. Several studies on the potential of OZ in the US northern Great Plains have been completed recently, though results have not been published. A brief summary of these studies follows, as well as discussion of some other strategies for reducing or eliminating tillage in organic farming systems in the region.

Organic zero-till in Montana

The efficacy of using a blade roller[49] and a 10% acetic acid solution in terminating a winter pea cover crop that was fall seeded directly into wheat stubble using a low-disturbance planter, and spring pea into a tilled seedbed, prior to seeding winter wheat, was determined in 2005 and 2006 at Bozeman (45.6797 lat., −111.0378 long., 1461 m elev.). The application of acetic acid at a 10% concentration was ineffective in killing the pea cover crops[50]. Combining multiple applications of acetic acid with blade rolling was effective in killing pea cover crop, although cost considerations likely prohibit this termination method from having commercial application on organic farms. The blade roller was ineffective in killing peas if cover crops were crimped–rolled when approximately 50% of plants had at least one open flower [pea growth stage Biologische

Table 1. Impact of cover crop termination method and species or species mixture on dry matter production of cover crops (CC) and weeds in 3 years at Dickinson, North Dakota, USA.

	2008[1]		2009		2010	
Tillage treatment	**CC**	**Weed**	**CC**	**Weed**	**CC**	**Weed**
	———	———	———	———	———	———
			–kg ha^{-1}–			
Disk	–[2]	309 b[3]	2839 b	589	2470 b	796 b
Sweep	–	196 b	2847 b	944	3796 a	1738 a
Roller	–	569 a	4256 a	404	3992 a	1677 a
P-value	–	0.005	0.019	0.146	< 0.001	0.012
Cover crop						
Hairy vetch (HV)	1728 c	584 a	702 c	1689 a	1633 b	2436 a
Winter rye (WR)	3615 a	153 b	4919 a	75 b	4052 a	640 b
Winter wheat (WW)	4113 a	274 b	3182 b	460 b	3821 a	800 b
HV + WR[4]	3535 a	286 b	4716 a	297 b	4039 a	717 b
HV + WW	2765 b	172 b	3052 b	342 b	3554 a	991 b
P-value	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001

[1] Cover crop treatments were established in the fall prior to the year in which data were collected.
[2] Termination methods were applied at the same vegetative growth stage in 2007–2008, and so aboveground dry matter production was determined for subplot treatments (cover crop species) but not whole plot treatments (termination method); disking was done prior to rolling in both 2008–2009 and 2009–2010 growing seasons, and so impact of whole plot and subplot treatments were determined.
[3] Different letters after numbers indicate that differences in treatment means were detected at $P < 0.05$.
[4] Cereal and legume components each were seeded at their sole crop rate in polycultures.

Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) 203[51]]. However, pea cover crop was killed effectively when crimped–rolled using the blade roller at the flat pod growth stage (growth stage BBCH 205[51]). Although not reported by Izard[50], grain yield approached 6700 kg ha^{-1} in 1 of 2 years where winter wheat was seeded directly into a winter pea cover crop that was killed at growth stage BBCH 205[51] using the blade roller (unpublished data).

Organic zero-till in North Dakota

Organic zero-till research in North Dakota has focused on identifying cover crop species and cultivars which provide adequate vegetative mulch when killed to suppress subsequent weed growth. A 3-year study at Dickinson (46.8792 lat., −102.7892 long., 735 m elev.) on loam soils compared dry matter production by weeds following five cover crop treatments terminated (i) mechanically without tillage using a blade roller, (ii) with non-inversion tillage using a Versatile 5000 blade plow[52] and (iii) with inversion tillage using a light tandem disk. The cover crop treatments were fall-seeded (late-September to mid-October, depending on the year) and included hairy vetch, winter rye (*Secale cereale* L.), winter wheat and combinations of each small-grain crop with hairy vetch, with cereal and legume components seeded at sole-crop rates in the mixtures. Above-ground biomass production of cover crops and weeds was determined from a 0.5-m^2 area in each plot just prior to imposing termination methods, which ranged from June 22 to July 2, depending on cover crop, method and growing conditions that year. Results demonstrated that winter rye produced equal or greater amounts of above-ground biomass compared with other cover crop treatments (Table 1). Weed production roughly 75 days after cover crops were killed ranged from 75 to 640 kg ha^{-1} in rye plots, whereas weed dry matter ranged from 584 to 2436 kg ha^{-1} in hairy vetch plots, depending on the year.

Termination of cover crops should be delayed until cover crops reach advanced growth stages when the blade roller is used. Otherwise, small-grain and legume plants may not be killed effectively[53,54]. In the study at Dickinson, small-grain cover crops were not killed effectively unless blade rolling was delayed until the early milk growth stage of kernel development (Zadoks growth stage 73)[55], and hairy vetch at the flat pod growth stage (BBCH growth stage 70)[51]. Delaying blade rolling compared with disking resulted in greater amounts of weed-suppressive vegetative mulch being produced in the study at Dickinson (Table 1). However, delaying killing of cover crops also allowed further growth of weeds that were established before termination methods were imposed, sometimes resulting in greater amounts of dry matter production by weeds following blade rolling compared with disking, as was the case in 2010. Delaying cover crop termination also prevented subsequent cash crops [buckwheat (*Fagopyrum esculentum* Moench), corn (*Zea mays* L.) and pinto bean (*Phaseolus vulgaris* L.)] from producing grain because too few heat units remained before fall freeze-up (data not presented). In contrast, disking needed to be done earlier than blade rolling or vegetative growth was excessive and interfered with effective kill of cover crop plants by inversion tillage methods (data not presented). Killing of cover crops by disking, if done early in the growing season, would allow subsequent crops to produce grain within one growing season.

Table 2. Effectiveness of blade rolling on termination of winter rye cultivars and dry matter (DM) production when rolling–crimping over a 3-year period at Carrington, North Dakota, USA.

	Visual termination rating[1]			DM production		
Cultivar	**2008**	**2009**	**2010**	**2008**	**2009**	**2010**
				$kg\,ha^{-1}$		
Aroostook	–	4.5	1.3 c[2]	–	2288	4639 b
Boreal	–	–	7.8 a	–	–	6284 a
Dacold	3.5 bc	9.3	4.9 b	7211	2340	5930 a
Exp. 1[3]	2.8 c	4.5	5.0 b	8123	3452	4663 b
Exp. 2[3]	1.5 c	–	–	8076	–	–
Hancock	–	5.0	4.7 b	–	2307	4185 b
Remington	6.8 a	–	–	6613	–	–
Rymin	4.3 ab	4.3	1.5 c	7643	2840	4078 b
Spooner	–	6.0	2.3 c	–	2329	3855 b
Wheeler	–	4.5	5.0 b	–	3089	4716 b
P-value	0.030	0.12	< 0.001	0.340	0.120	0.004

[1] Rating scale was from 1 to 10 where 1 = no plants killed and 10 = all plants killed with ratings assigned approximately 30 days after blade rolling.
[2] Different letters after numbers indicate that differences in treatment means were detected at $P < 0.05$.
[3] Experimental cultivars being considered but not available for commercial use.

A 3-year study at Carrington (46.4497 lat., −99.1261 long., 484 m elev.) on loams soils compared ten winter rye cultivars for dry matter production just prior to rolling with a blade roller in fields with soil nitrate levels at seeding ranging from 48 to 73 $kg\,ha^{-1}$. The rye treatments were planted at 247 live kernels m^{-2} on September 18–28, depending on the year. Rye was rolled at early anthesis (Zadoks growth stages 60–62)[55] on June 14–23, depending on the year and cultivar treatment. The cultivars Boreal and Dacold both produced roughly 6000 $kg\,ha^{-1}$ in 2010, compared with less than 5000 $kg\,ha^{-1}$ for the other cultivars that were grown (Table 2). Dry matter production differences were not detected among a subset of the ten cultivar treatments in 2008 and 2009, which included Dacold. Results also demonstrated the inability of blade rolling to kill a winter rye cover crop consistently when termination was attempted at early anthesis. These results demonstrated that cultivar selection can affect dry matter production by cover crop species in some environments, but other factors confound cultivar recommendations when growing winter rye for production of weed-suppressive vegetative mulch across environments.

Organic zero-till in South Dakota

The importance of crop diversity in developing OZ systems has been considered in South Dakota. Anderson[56] discussed conceptually how diversifying crop rotations and other cultural practices could be used to control weeds in organic farming, thereby reducing the need for tillage. This researcher cited previous work in conventional zero-till systems where rotations consisting of two cool-season crops followed by two warm-season crops resulted in lower weed densities than all other rotations considered[57]. The importance of 'stacking' two consecutive phases of crops with similar life cycles was the most efficacious in controlling weeds because it balanced the natural temporal decline in weed seed density with the population increase of weeds during the growing season. The contrast in crop life cycles helps minimize seed production of weeds of contrasting life cycles, i.e., warm-season weeds in cool-season crops. No-till enhances the benefit of this rotational design in reducing the number of live weed seeds in soil. Anderson[57] discussed the benefits of no-till farming on weed control, noting that crop residue on the soil surface suppresses weed germination and seedling establishment directly, and also indirectly by exposing unburied weed seed to predation and environmental extremes. He concluded his concept paper[56] by suggesting that rotations that include crops with different life cycles, perennial forages and intervals of no-till should be part of an integrated strategy for controlling weeds in organic farming systems.

Recommendations for OZ Research in the US Northern Great Plains

Preliminary results of OZ studies in the northern Great Plains indicate that cover crops can be killed mechanically without tillage if termination methods are delayed until crops reach advanced growth stages in late spring or early summer. However, this delays the planting of subsequent cash crops and prevents maturation of annual crops before the onset of the first killing frost in the fall. Alternative strategies must be developed so that cash crops can be grown successfully following termination of cover crop

growth. This could involve selecting cover crop species that can be terminated earlier, or adjusting crop rotations to include winter annual cash crops that are planted in the fall after cover crop termination and harvested during the following growing season.

Researchers in Canada have had success in killing spring-planted annual cover crops in late summer or fall and then seeding a cash crop the following spring[49]. This strategy should be explored within the US northern Great Plains and should include the screening of cover crop species adapted to OZ systems that encompass multiple years and growing seasons. Tillage implements that kill cover crops effectively but with minimal burial of vegetative mulch, such as the blade plow[52], should be investigated as tools to control weeds between crop plantings in OZ farming systems.

Weed control will continue to be the greatest obstacle for successful adoption of OZ methods among organic farmers. Perennials pose a particular challenge since it is unlikely that any amount of crop residue mulch produced by killed cover crops under actual field conditions could be thick enough to suppress weed species like Canada thistle [*Circium arvense* (L.) Scop.] and field bindweed (*Convolvulus arvensis* L.). Use of forages in rotations with cash grain crops for the purpose of weed control is a widely documented practice in the Great Plains[58], and establishment of alfalfa pasture has been used effectively to control Canada thistle in the region[59]. However, perennial forages pose the same challenges as perennial weeds to organic farmers wanting to convert perennial stands back to crop land without tillage. Livestock grazing in forage pasture, on crop aftermath and weeds after cash grain crop harvest, or at other selective times can also be used to control perennial weeds and, conceptually, could be used to weaken perennial forages so they are prone to winterkill in the northern Great Plains. The ability of livestock to kill perennial forage pasture consistently through targeted grazing requires greater attention in the region and, if successful, could be an important part of an integrated strategy for controlling weeds in OZ farming systems.

Synthetic herbicides are an important weed control tool in conventional systems, but are not allowed in organic farming systems. Although many organic farmers oppose the use of herbicides for controlling weeds philosophically, some bio-herbicides are comprised of substances that are allowed for use in certified organic systems. These bio-herbicides, including an experimental compound reportedly with systemic activity but not yet commercialized, are being field-tested in North Dakota (data not presented) and may offer organic farmers who are not opposed to the infrequent use of bio-herbicides an additional weed control tool in OZ systems. Future research should focus on integrating cover crops with forages, grazing, the judicious use of high-residue tillage equipment and approved bio-herbicides in developing a multi-faceted weed control program for use in OZ farming systems in the US northern Great Plains.

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Conservation tillage for organic agriculture: Evolution toward hybrid systems in the western USA

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Abstract

Organic farming has been historically dependent on conventional tillage operations to convert perennial pasture leys to annual crop rotations, incorporate crop residues, compost and cover crops, as well as to mechanically kill existing vegetation. Conventional tillage, however, has long been known to lead to soil degradation and erosion. A recently developed no-till organic production system that uses a roller–crimper technology to mechanically kill cover crops was evaluated in two states in the western United States. In Washington, pumpkins (*Cucurbita* spp.) grown in a no-till roller–crimper (NT-RC) system produced yields 80% of conventional tillage, but with fewer weeds. However, in California on-farm research trials in organic cotton (*Gossypium barbadense* L.), tomato (*Lycopersicon esculentum* Mill.), eggplant (*Solanum melongena* L.) and cowpea (*Vigna unguiculata* (L.) Walp.), the no-till system produced virtual crop failure, or yields less than 20% of the standard production method. The major problems associated with rolled cover crops in California included reduced crop seedling emergence, planter impediment with excessive residue, lack of moisture and delay in transplanting of vegetable crops due to continued growth of cover crops, in-season crop competition from cover crop regrowth and impracticability of using cultivators. Further, excessive dry residue during summer in California can present the risk of fire. In both California and Oregon, considerable success has been demonstrated with zone tillage (strip tillage) in conventionally produced field and vegetable crops. In a replicated Oregon trial, the organic strip tillage treatment produced 85% of the broccoli (*Brassica oleracea* L.) yield compared to a conventional tillage treatment. Our studies suggest that the zone tillage concept may offer opportunities to overcome many of the agronomic challenges facing no-till.

Keywords: no-till, strip-till, zone tillage, conservation tillage, roller crimper, organic weed management, cover crops, *Secale cereale* L., *Phacelia tanacetifolia* Benth

Introduction

Conserving and enhancing soil quality has long been a philosophical cornerstone of the worldwide organic agriculture movement. With the creation of the US National Organic Program (NOP) in 2002, this philosophy became part of the federal laws regulating organic farming. Section 205.203 of the NOP[1] requires that 'The producer must select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion'. Similarly, the International Federation of Organic Agriculture Movements standards[2] also require minimum tillage and other practices to prevent soil erosion and degradation.

Organic farming has been historically dependent on conventional tillage operations to convert perennial pasture leys to annual crop rotations, incorporate crop residues, compost and cover crops, as well as to mechanically kill existing vegetation. Preparing a relatively smooth, residue-free seedbed is essential for precision mechanical weed control in many organically grown crops. Conventional tillage, however, leaves the soil exposed to wind and water erosion, and has been shown to reduce soil aggregate size and accelerate the oxidation of soil organic matter[3,4]. The multiple passes over a field with conventional tillage are labor and energy intensive[5], contribute to soil compaction and generate airborne particulate matter[6].

Direct seeding of a crop into herbicide-killed crop residue, also known as no-till, has been documented in

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conventional agricultural systems to dramatically reduce soil erosion, and improve several key components of soil quality, as well as reduce machinery, labor and fuel costs[7,8]. In a 28-year comparison of no-till and conventional tillage in Ohio, for example, no-till systems had higher levels of organic carbon, aggregate diameter and water-holding capacity than conventional tillage systems[9]. In numerous studies, no-till systems have produced comparable or improved yields to conventional tillage, although yield response frequently depends on the crop and climatic region[10–12].

Some authors have suggested that because of the intensive tillage requirements of organic systems, conventional no-till agriculture may provide superior economic, agronomic and environmental benefits compared with organic farming[13]. There has been, however, widespread interest in no-till and reduced tillage systems among organic farmers and researchers, as demonstrated by numerous workshops and conferences in the United States and Europe in recent years. Much of the focus in the United States has been on an organic no-till planting system that uses a 'roller–crimper' to suppress a cover crop[14–16]. Although cereal rye (*Secale cereale* L.) is commonly used as a cover crop, various cover crop species and mixtures have been used in this system. A traditional no-till planter is used to plant the crop through the 'rolled down' cover crop mulch. The mulch serves to suppress weeds and conserve soil moisture. In this paper, we will refer to this system as the no-till roller–crimper (NT-RC) system.

Although this approach has shown potential for organic soybean (*Glycine max* L.) production in the mid-Atlantic region[17], and to some extent for no-till soybean production in the Midwestern US[18], it has shown limited success for field corn[19]. In this paper, we present preliminary evaluation of the NT-RC system in Washington and California, and discuss fundamental agronomic constraints and risks facing no-till organic farming. We also present work in Oregon on zone tillage systems for organic vegetable crops.

2009 Washington On-farm No-till Pumpkin Research

An on-farm experiment was conducted near Woodinville, WA to compare two tillage treatments: (1) standard tillage with a rototiller and (2) rolling/crimping the cover crop[20]. All plots were tilled and planted to cereal rye in September 2008, and the tillage treatments were implemented when approximately 75% of the cover crop was at full flower. Cover crop was incorporated into the rototilled plots on May 31, 2009 and no-till plots were rolled/crimped on June 2, 2009. The cover crop regrew in the rolled/crimped plots within 2 weeks, so these plots were rolled/crimped again on June 16, 2009. Tilled plots were rototilled again prior to transplanting pumpkins on June 27, 2009. Pumpkin yields in the no-till plots (7.2 Mg ha^{-1}) were 20% less than the rototilled plots (9.8 Mg ha^{-1}); however, yields were not statistically different at a 0.05 level of significance[20].

In the Washington trial, soil quality parameters measured in mid-August indicated that the tilled plots had significantly lower bulk density (i.e., 'lighter' soil) and more rapid infiltration than in the no-till plots. According to the authors, 'these short-term improvements in soil quality from rototilling may have resulted in more immediate vigorous pumpkin growth (observed visually) and yield, although this was not significantly different between treatments.' The authors point out that improvement in soil quality through tillage reduction and unincorporated cover crop residue occur over the longer term, and are rarely measured within one growing season.

Organic No-till Experiences in California

Several experimental trials and farm demonstration evaluations of the NT-RC system have been conducted at various sites in California's Central Valley during the past 5 years. These studies have evaluated cover crop termination using a 5 m-wide roller–crimper for production of Pima cotton, tomato, eggplant and cowpea. This work was initiated in 2006 at four sites: Five Points, Madera, Capay and Parlier, CA.

Cotton

At Five Points, an experiment was established to compare conventional tillage with NT-RC systems for conventional cotton production. Treatments included: (1) conventional tillage (beds prepared in winter, trifluralin applied pre-emergence in fall, spring cultivation, and re-shaping and preparation of beds); (2) stale seedbed (beds prepared in winter, spring burndown with paraquat with no further cultivation or bed shaping); (3) NT-RC system using cereal cover crop mixture of cereal rye (cv. Merced) and triticale (x *Triticosecale*) cv.Trios 102; and (4) NT-RC system using a legume cover crop mixture of Balansa clover (*Trifolium michelanium* L.), Persian clover (*Trifolium resupinatum* L.) and Austrian winter pea (*Pisum sativum* spp. *arvense* L.). No herbicides were used in the NT-RC treatments 3 and 4. The experimental design was a randomized complete block with four replications. Each treatment plot was 5 m wide and 100 m long. Cover crop mixtures of cereals or legumes were planted in October 2005 and rolled/crimped at an appropriate maturity stage[21] on April 24, 2006 using the front-mounted roller–crimper. Pima cotton was planted directly behind the roller–crimper with a John Deere 1730 no-till seeder in the same operation. The same planter was used to plant the conventional tillage and the stale seedbed plots.

Results. Although the roller–crimper appeared to kill the cover crop, the crop seedlings took nearly 3 weeks to emerge following the rolling operation due perhaps to cooler temperatures under the cover crop mulch, and

continued growth of the cover crop during this time resulted in the soil surface becoming quite dry. This likely reduced the cotton crop germination and emergence. The cover crop plots were then flood irrigated to enhance crop emergence but the stand count was still 90% less than that in the conventionally planted or the stale seedbed cotton plots. Aboveground biomass samples taken on May 31 showed that the cotton dry mass in the conventional and stale seedbed plots was 30 times more than that in either of the cover crop treatments. There was no significant ($P < 0.05$) difference in cotton stands or biomass between the cereal and legume cover crop treatments (data not shown). While these plants eventually grew, they did not mature early enough to be harvested. Thus, there was no marketable yield from the rolled/crimped cover crop plots at this site. Weed density samples taken on May 31 showed that the cover crops had similar weed densities as the conventional plots, ranging from 2 to 3 plants m^{-2}. The stale seedbeds, however, had greater ($P < 0.05$) weed densities (13–16 plants m^{-2}) than the cover crop or the conventional plots. The cover crop plots demonstrated that these treatments could provide as much weed suppression without herbicides as the conventionally tilled plots with herbicides. However, acceptable crop stand establishment was not achieved. Therefore, if such a cover crop system were to be adapted for cotton in California, earlier and complete termination of the cover crops is needed, or perhaps zone tillage may be more appropriate than no-till and necessary measures have to be taken to prevent continued cover crop regrowth.

Eggplant

At the Madera organic farm site (36.96°N 120.07°W), similar mixes of cover crops were rolled with the roller–crimper before hand transplanting eggplant, and this system compared with the organic farmer's traditional system of plasticulture eggplant production. As in the Five Points experiment, the cover crop was easily rolled down; however, it took 3 weeks for the cover crops to eventually die. This resulted in a 4-week delay in transplanting the eggplant in the cover crop plots compared to the traditional plastic culture system. The rolled cover crop plots yielded about 20% of the eggplant production of the plastic system.

Tomatoes

At another organic farm site near Capay (38.71°N 122.05°W) the same cover crop mixes were compared with a farmer's customary hairy vetch (*Vicia villosa* Roth.) cover crop within a tomato transplant system. Data were collected for cover crop growth and percent cover crop kill following rolling. Similar observations were made at this site as at each of the two other sites. It took about 3 weeks more for the rolled cover crops to fully die compared to the farmer's customary system. This in turn delayed the transplanting and eventually the study was abandoned due to a poor crop stand.

Cowpeas

In 2007–2008, a study was conducted in cowpea at Parlier (36.6°N 119.53°W). Treatments included conventional tillage with or without herbicide and no-till rolled cover crops with or without herbicide. The experimental design was a split-plot, with tillage as the main plot and presence or absence of herbicide as the sub plot. The treatments were replicated four times; each main plot was 61 m long and 18.3 m wide. The plots were split into 30×18.3 m subplots. A cover crop mixture of oats (*Avena sativa* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) was planted in October 2007 and irrigated as needed. On April 15, 2008 when the cover crop mixture had reached an optimal level of maturity, it was rolled using the roller–crimper. Beds 75-cm wide were then prepared as is customarily done in the conventional tillage plots. Beds were not made in the cover crop plots. On May 29, cowpea seeds were planted in the conventional tillage beds using a John Deere Flex planter. In the no-till plots, cowpea was drill-seeded into the rolled cover crop plots using a Sunflower 1540 no-till drill at 18-cm row spacing. Seeding rate was 67 kg ha^{-1}. Crop seedling emergence was poor in the no-till plots because of 'hair pinning' of the cover crop, which is the pressing of cover crop residue into the slot created by the disk openers on the no-till planter. This produces poor seed-to-soil contact for the crop seeds. The cowpeas were re-planted using a John Deere 1530 no-till seeder on June 10. During this no-till seeding operation, hair pinning occurred again and the planter's residue managers were used to push away the cover crop from the seed row in front of the planter disk. Better cowpea stand was achieved when the residue manager was used. Bentazon herbicide was applied at the first trifoliate stage of the crop at 1.6 liter ha^{-1} and incorporated with sprinklers immediately after application. Cowpea and weed dry biomass were determined on July 21. Plants were cut on September 24 and harvested on October 16.

Results. The conventional tillage treatments with herbicide had almost no weeds, whereas weed biomass in the plots without herbicides ranged from 12 to 20 g m^{-2}. Weed biomass in the no-till plots with or without herbicides was significantly ($P < 0.05$) greater than in the conventional tillage plots, ranging from 55 to 96 g m^{-2} in the plots with herbicide and 154 to 331 g m^{-2} in the plots without herbicides. More than 90% of this weed biomass represented continued growth or regrowth of the cover crop. Cowpea dry biomass in the conventional tillage plots with or without herbicides was about 2.5 times greater than that over the rolled cover crop mulch. Cowpea yields were approximately 40% lower in the cover crop plots than in the conventional tillage plots (data not shown). Therefore, the cover crop not only impeded and delayed crop emergence but also served as a weed,

resulting in cowpea yield loss. In summer, in a dry environment like California, excessive dry residues on the surface can also pose fire hazards, especially in organic production systems that rely on flame weed control.

The No-till Roller-crimper System: Constraints

From our experiences with the NT-RC system in the western United States, as well as in following the development of this system in other areas of the country, we believe this system has major agronomic constraints that limit its adoption by organic farmers. Understanding these constraints is critical for improving the performance of this system, or in knowing when to select other tillage systems when they are better suited.

The NT-RC approach is predicated on several components, including: (1) producing a 'high biomass' cover crop; (2) adequately killing the cover crop (and other weeds) with the roller–crimper prior to planting; (3) achieving a satisfactory cash crop stand by no-till drilling into the rolled cover crop residue; (4) providing adequate mineral nutrition to the cash crop; and (5) managing weeds and other pests in the cash crop.

Producing high cover crop biomass

Most of the work on the NT-RC approach has stressed the need for 'high biomass' of the cover crop before rolling to provide a sufficient level of mulch on the soil surface to control weeds. McLenaghen et al.[22] reported that weed suppression by cover crops was directly proportional to the amount of cover crop growth. Smith et al.[17] suggested that at least $9000\,kg\,ha^{-1}$ of dry matter biomass is required for adequate weed control. In a factorial experiment examining the impact of N fertilizer rate (from poultry manure) and the seeding rate of the rye cover crop on cover crop biomass and weed suppression, Ryan et al.[23] found increasing rates of N increased rye biomass, but did not reduce weed biomass. Increasing seeding rates of rye did not increase rye biomass, but did reduce weed biomass. These authors suggest that the early spring ground cover obtained with the higher seeding rates was key in reducing weed levels.

Establishing a solid cover crop stand in the fall is necessary to smother winter annual weeds, as well as to have uniform ground cover in the spring for the roll down operation. Since the rolled-down, dead cover crop biomass is expected to provide weed control across the soil surface, any openings in the cover crop stand can allow weed growth. Also in regions where the cash crop is typically harvested late in the season, soils are frequently too wet for fall tillage. Cover crops are planted late or not at all. Usually late-planted cover crops do not produce adequate spring biomass for weed suppression in the NT-RC system[24].

Killing the cover crop with the roller–crimper

Effectiveness of the roller–crimper to kill the cereal rye cover crop is dependent on the stage of maturity of the rye. Rye must be at least at Zadoks growth stage 61 (anthesis) to obtain 'effective control' of at least 85% kill with the roller[24]. If the rye is rolled at earlier maturity stages, the rate of suppression falls quickly. This translates to rolling the cover crop fairly late in the growing season—late May or early June for Pennsylvania and other northern locations[19]. These late planting dates will necessarily result in lower crop yields than longer season varieties planted earlier. For farmers trying to produce crops for the fresh market, delays in planting are even more costly from loss of market share.

In work at Pennsylvania State University, Mirsky et al.[24] examined the effect of fall planting date of a cereal rye cover crop on the effectiveness of the roller–crimper to kill the rye in the following spring. Rye planted on August 25 was 79% killed by the roller–crimper; however, only 73% of the rye was killed in the spring following a September 15 planting, with rye suppression dropping to 63% following the fall planting date of October 5.

Although the roller–crimper usually achieves a uniform 'laying down' of the rye cover crop in the field, the cover crop usually does not die until several weeks after rolling. In California's production environments, for example, irrigation is typically needed to establish most cash crops. The timing and application method of this irrigation need to be refined in order to accommodate the cover crop rolling operations so as to allow the cover crop to quickly die and the subsequent crop to successfully emerge and establish.

Achieving a satisfactory crop stand

The no-till seeding of a cowpea crop into the rolled cover crop in California was not successful due to hair pinning of the rolled residue. Using a no-till planter with residue managers achieved some improvement in crop stands, but the movement of residues out of the drilled row also increased weed germination. Although rye was not used in this study in California, it has well-known allelopathic chemicals that can also suppress germination and growth of crops as well as weeds[25–28].

Providing adequate crop nutrition

Most organic fertilizer materials (composted manures and animal by-products) tend to be in solid form, and soil incorporation is typically used to increase N mineralization and crop uptake. Soil incorporation also reduces N loss to the atmosphere through ammonia volatilization. Soil incorporation of amendments is impossible in the NT-RC system, however, unless they are applied in the fall preceding cover crop seeding.

Although the NT-RC approach has promise for organic soybean production, success has been limited for corn (*Zea mays* L.) and other crops requiring relatively high levels of N input for maximum yield. This is likely explained by the immobilization of N by the cereal rye cover crop that will have a very high carbon to nitrogen (C:N) ratio in the tissue when it is flowering. In a North Carolina study[29], soil N was immobilized for 6 weeks following a rolled and crimped rye cover crop. These authors suggested that the 'induced low nitrogen environment' was also a key factor in the weed reduction under the rolled rye. Angustia[30] also showed that high C:N ratio cover crops suppressed weeds when tilled into the soil, but that this weed-suppressive effect was eliminated with application of N fertilizer.

A major constraint of the NT-RC system with a rye cover crop is the inability to include a legume cover crop into the mixture to supply biologically fixed N. Numerous authors have documented N contributions to the following cash crops following legume cover crop mixtures and ecological synergism that occurs in a cereal–legume mixture[31,32]. The cereal scavenges soluble nitrate from soil that would otherwise be lost through leaching from the soil, and serves as a physical trellis to hold up the legume as it grows. The legumes also provide a significant amount of N to the rye during the growing season.

The problem of including legumes with the rye in the NT-RC system is the differing crop phenologies, particularly the timing of the stage of growth necessary for killing the legumes using the roller–crimper. In work in Pennsylvania, Mischler et al.[33] examined the impact of the timing of roller crimping on regrowth of hairy vetch. Vetch needed to reach the early pod-set stage to achieve a complete kill, but in Pennsylvania this did not occur until the second or third week of June. According to the authors, this is approximately 4–6 weeks after recommended corn planting dates, and this delay is likely to limit corn yield potential due to a reduced length of growing season and smaller accumulation of heat units for the corn.

The delay of planting date for the NT-RC system eliminates many of the crops planted in California and the Pacific Northwest. With California's relative mild winters, growers are able to start cropping relatively early in the season (i.e., March–April) and waiting for a rye or rye/vetch cover crop to reach a stage where it can be killed by the roller–crimper means 4–6 weeks of lost crop growth and economic return. In the cool, wet Pacific Northwest (west of the Cascade Mountains), similar problems occur. Most annual vegetable crops must be planted much earlier than the NT-RC system allows if the cover crop is going to be killed with the roller.

The use of cover crops in annual cropping systems in California's Central Valley is not currently widespread due largely to concerns about additional costs associated with cover crop management and limitations of available water needed for successful cover crop establishment and production. Studies in Five Points, California in western Fresno County, however, have shown that when no irrigation water is used to establish cover crops, biomass production depends closely on the amount of winter rainfall that occurs from October to March. Thus, farmers who have integrated cover crops into their annual cropping systems in this region for crops such as tomatoes, now tend to expend 10–15 cm of fall irrigation water to establish the crops prior to the onset of winter rains[34].

Controlling weeds and other pests

Ironically one of the primary reasons for developing the NT-RC system was to use the rolled down mulch for weed control, however, one of the largest challenges to the NT-RC system is weed management. The rolled down mulch must be of sufficient biomass and uniformly distributed across the soil surface to achieve optimum weed suppression. Frequently the mulch will not suppress all of the weeds, and there are weed escapes. For example, Curren et al.[19] considered 85% weed suppression in the NT-RC system as 'acceptable.' Also the no-till planter opens up a small slot where weeds can emerge within the crop row. In the NT-RC system, however, there are no opportunities for mechanical weed control to provide 'rescue' control for these weed escapes. For example, field bindweed (*Convolvulus arvensis* L.) is a common weed in many annual crops in California, including tomatoes, beans and cotton. In many cases, cultivation is the most effective method of control of this prostrate, vining species. Hand hoeing through the cover crop residue is difficult, and hand weed pulling is frequently required.

In the Pacific Northwest, cover crops can provide an excellent habitat for slugs[35] and rodents such as the meadow vole (*Microtus* sp.). Both slugs and voles are major economic pests of a broad array of crops, and few effective control practices are available for organic growers. This can be a severe limitation to adoption of conservation tillage systems that leave more than 30% crop residue on the soil surface, including both the NT-RC system and the zone tillage systems that will be described. In California, there are no reports of vertebrate pest populations in rolled down cover. However, studies have shown vertebrate pests such as gophers (*Thomomys* sp.) were more abundant in orchards and vineyards that had cover crops[36,37].

Zone Tillage: A 'Hybrid' Tillage System

Zone tillage (also known as strip tillage) is a form of conservation tillage that clears a narrow zone of soil, loosening subsoil layers and preparing a seedbed, while areas between the tilled strips receive shallow or no tillage[38,39] (Fig. 1). Zone tillage has been used extensively in the Midwestern United States to overcome many of the

Figure 1. Zone tillage involves separate tillage, weed control and fertilizer operations for the crop zone and the between-row zones. The shank/coulter strip tillage machine shown here tills strips approximately 25 cm wide and 30 cm deep.

yield-reducing impacts of no-till in conventional farming systems[40]. We consider zone tillage to be a hybrid tillage system, integrating aspects of conventional tillage and no-till.

In zone tillage, there are two distinct zones of tillage activity: (1) the crop zone, typically 20–30 cm wide, where tillage, fertilizer and weed management are intensified; and (2) the between-row zone that is managed less intensively, and with different objectives. In conventional tillage systems, the entire surface of a field receives multiple passes of various kinds of tillage equipment to prepare a uniform soil surface for planting and subsequent cultivation operations. In strip tillage systems, however, with a typical 75- to 90-cm row spacing, tillage occurs on only 35–40% of the soil surface. Crop residue is mixed with the soil in the tilled strip, accelerating a beneficial release of N through microbial mineralization of organic matter. The area between the tilled zones (between row) is managed independently, depending on the nature of the crop or cover crop residue. Surface residues remaining between rows are critical to reduce soil erosion.

Zone tillage decreases both the area and volume of soil that is disturbed on each tillage operation, reducing the amount of dust that is typically generated in intercrop tillage[41]. Fuel, labor and equipment costs are also reduced when compared to conventional tillage[42,43]. Soil compaction from tractor wheel traffic is confined in zone tillage, dramatically reducing compaction in the crop growth zone.

Oregon and California Experiences with Conventional Strip Tillage

In a replicated 4-year study in the Oregon Willamette Valley, 20 on-farm trials were conducted comparing strip-tillage systems with conventional tillage systems for sweet corn production. In the first 2 years of the trials a 4.5 m Northwest Tillers® rototiller, modified to till 6 rows 20 cm wide was used. In the later 2 years of the trials, a strip-till machine using a shallow shank and rolling coulters was used. Across an array of soils and crop residue situations, sweet corn yields from strip-tillage and conventional tillage systems were identical in each year of the 4-year trial. However, machinery and labor costs were reduced by nearly 50% by strip-tillage[38].

In California, a range of economic and natural resource conservation benefits have attracted dairy farmers, in particular, to strip tillage. This system uses fewer intercrop tillage passes or operations than traditional tillage systems thereby reducing 'land preparation' costs. In a 2002 farm evaluation of strip-tillage forage-corn production near Modesto, CA, the land preparation costs were about 54% lower than the costs of traditional preplant soil preparation[39]. The requirements for farm labor and the time required for tillage between crops was also lower and time between successive forage crops was reduced. This allowed more opportunities for 'triple-cropping', the sequential production of three crops within a given calendar year. However, these were not organic production systems.

Organic Strip Tillage Broccoli Production

To evaluate strip tillage for organic production systems, a randomized block experiment was established in 1998 at the Oregon State University (OSU) Vegetable Research Farm near Corvallis[44]. A conventional tillage treatment (using a Tortella® reciprocating spader and a Lely® roterra to prepare the seedbed) was compared with a strip–till system using a Northwest Farm Tillers® 3.7-m rototiller modified to till four 15 cm-wide strips approximately 15 cm deep on 75-cm row centers. Cereal/vetch cover crops, planted the previous October, were suppressed using a flail mower prior to imposing tillage treatments. Granular fish fertilizer was manually applied in 15-cm band over each crop row and incorporated using the strip tiller prior to planting in both tillage treatments. Broccoli (cv.= 'Arcadia') was transplanted on May 28 and irrigated as necessary through the season. Two weed management treatments for the between row areas in the strip tillage treatments were evaluated in a split-plot design. These included: (1) 'cultivated' with a Buffalo® high residue V-sweep cultivator (Fleischer Manufacturing, Columbus, NE); and (2) mowed with a walk-behind trimmer mower (DR Power Equipment, Vergennes, VT). Mowing was conducted on June 14 and June 27. The reduced tillage and the strip till plots were cultivated with the Buffalo cultivator on June 27. Weeds within the rows were controlled by hand hoeing on July 1 and 7.

Broccoli yield estimates were made by cutting, grading and weighing heads on August 10 and 16. Weed abundance was estimated on June 23 (25 days after transplanting broccoli and before the between-row cultivation in the strip-till, cultivated plots).

Results

The conventional tillage treatment produced significantly higher broccoli yield (11,500 kg ha^{-1}) than both the strip-till cultivated (9810 kg ha^{-1} and the strip-till mowed (9320 kg ha^{-1}) ($P<0.05$). Densities of purslane (*Portulaca oleracea* L), hairy nightshade (*Solanum sarrachoides* Sendtner) and Persian speedwell (*Veronica persica* Poir) were all greater in the between-row areas of the conventional tillage plots than in between-row areas of the strip-till plots ($P<0.05$)[44].

Discussion and Conclusions

Although the NT-RC system has shown potential for production of organic soybeans in the mid-Atlantic region of the USA, and for some late-planted crops in other regions, we believe there are major agronomic constraints that ultimately limit the application of this system in organic agriculture. There are significant risks of crop failure or economically significant yield loss associated with the NT-RC system because of these problems. Future research should address these constraints to improve the productivity and reliability of this system.

We suggest that the zone tillage concept offers opportunities to overcome many of the agronomic challenges faced with the NT-RC, as well as to reduce the risk of crop loss. We do not present any 'off the shelf, ready-to-go' zone tillage systems for organic agriculture. Numerous technical and agronomic challenges must be met before zone systems become operational. There are, however, obvious advantages to zone tillage compared to the no-till approach that may allow a broader adoption by organic farmers in multiple scales of production.

A variety of tillage implements can be used in the tilled 'crop' zone to achieve specific tillage objectives, including breaking of soil compaction layers, killing and incorporating existing vegetation into the soil, and preparing a fine seedbed for precision planting. For example, 'second-pass' zone tillage equipment can be used to perform minimum-tillage finishing operations in the tilled zone[45] (Fig. 2). Organic fertilizers can be band-applied and mechanically incorporated into the strip, and later side-banded based on crop needs. Precision flaming[46] (Fig. 3), stale seedbed techniques, and precision mechanical cultivation technologies can be used to manage weed populations in the crop zone[47]. Weeds and cover crop regrowth in the between-row zone can be managed by a combination of mowing, cultivating or other shallow tillage, depending on the crop and soil situation.

Clearly, there are challenges to the adoption of zone tillage systems by organic farmers. The need for new, specialized equipment is a formidable barrier, both in terms of availability and cost. A list of specialized equipment might include: (1) a primary strip tillage machine, such as the shank/coulter strip tiller described earlier; (2) a 'second-pass' finishing machine, often needed to prepare a seedbed suitable for planting; (3) a strip fertilizer and compost application machine, needed for zone fertilization; (4) strip flamers and thermal weed control technologies; (5) precision in-row cultivation equipment; and (6) strip-mowers, high-residue cultivators and undercutters to manage weeds and cover crop regrowth in the between-row areas. This can represent a significant investment in specialized equipment, and some of this equipment is not yet available commercially.

Additional research is needed on novel cover crops and cover crop mixtures to facilitate organic conservation tillage systems. For example, *Phacelia tanacetifolia* Benth., an annual native of the southwestern USA, has shown promise as a substitute for the cereal crops when grown with common vetch in Oregon (Luna, unpublished data). *Phacelia* is much easier to kill mechanically, and the residue and roots are easy to incorporate into the tilled zone. *Phacelia* is not adapted to cold winter temperatures, however, which limits its range of utility.

Curren et al.[19] emphasized that continuous no-tillage was not going to be possible in organic systems. Nor is zone tillage suggested here as a continuous system.

Figure 2. A second-pass strip tillage machine was developed by Hendricks Farms (Stayton, OR) and modified by Pearmine Farmers (Gervais, OR). Multiple gangs of parallel disks and a sprocket roller break up soil clods to prepare a seed bed within the tilled crop zones.

Figure 3. A strip flamer, developed by Charles Merfield and modified by Edward Peachey at Oregon State University, can be used in organic zone tillage systems to reduce weeds in the crop row.

Rather, no-till and zone tillage are conservation tillage options that could be used at specific points in the crop rotation cycle. As Peigné et al.[47] emphasized, the success of conservation tillage systems for organic farming depends on the choice of crop rotation to enhance pest and nutrient management.

Minimum or reduced tillage practices will continue to be needed in organic farming systems for a wide array of agronomic and economic reasons[48]. Research is needed to develop a more prescriptive approach to minimum tillage, which would integrate various tillage tools to address specific crop production and environmental goals. By focusing on the specific goals of each separate tillage operation (i.e., breaking up soil compaction, killing existing vegetation), a suite of equipment can be used to minimize detrimental impacts as well as tillage costs.

There will be inexorable trade-offs between agronomic and economic imperatives, and the desires to conserve and improve soil quality. Such is the ongoing dialectic of developing sustainable agricultural systems. Conservation tillage for organic agriculture will require a more integrated, holistic approach to optimizing cover cropping and tillage systems for the specific crops, soils and climatic regions of the world.

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Conservation tillage issues: Cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA

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Abstract

Organic producers in the mid-Atlantic region of the USA are interested in reducing tillage, labor and time requirements for grain production. Cover crop-based, organic rotational no-till grain production is one approach to accomplish these goals. This approach is becoming more viable with advancements in a system for planting crops into cover crop residue flattened by a roller–crimper. However, inability to consistently control weeds, particularly perennial weeds, is a major constraint. Cover crop biomass can be increased by manipulating seeding rate, timing of planting and fertility to achieve levels ($>8000\,kg\,ha^{-1}$) necessary for suppressing summer annual weeds. However, while cover crops are multi-functional tools, when enhancing performance for a given function there are trade-off with other functions. While cover crop management is required for optimal system performance, integration into a crop rotation becomes a critical challenge to the overall success of the production system. Further, high levels of cover crop biomass can constrain crop establishment by reducing optimal seed placement, creating suitable habitat for seed- and seedling-feeding herbivores, and impeding placement of supplemental fertilizers. Multi-institutional and -disciplinary teams have been working in the mid-Atlantic region to address system constraints and management trade-off challenges. Here, we report on past and current research on cover crop-based organic rotational no-till grain production conducted in the mid-Atlantic region.

Key words: cover crops, organic no-till, high-residue cultivation, subsurface banding, rotational no-till

Introduction

The mid-Atlantic region, when compared with other US agricultural sectors, is composed of small (average farm size is 73 ha), diversified cropping systems and integrated animal and crop production systems. Approximately 29% of land in the region is used for agricultural purposes, and livestock production composes the majority of revenue earned in the top five commodities in the region[1]. Soil conservation is a priority for growers in the region due to shallow soils with relatively low organic matter, high soil-erosive potential, and water quality concerns regarding the Chesapeake Bay and other estuaries. Interest in and use of cover crops are increasing rapidly in the region as a result of these concerns because annual precipitation is relatively high (760–1012 mm, evenly distributed throughout the year); spring moisture is usually not a constraint in the mid-Atlantic region.

Organic grain production in the mid-Atlantic region relies on extensive soil disturbance for weed management and requires relatively large amounts of diesel fuel and labor. Dependency on cultivation also creates a disproportionally greater risk of weed control failure due to abundant or untimely rainfall during crop establishment. Reducing tillage in organic grain production systems has the potential to reduce soil erosion, improve soil quality,

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increase soil carbon (C) sequestration, decrease greenhouse gas (GHG) emissions and reduce energy requirements relative to traditional organic-production methods. While continuous and rotational conventional no-till crop production has been widely practiced in the mid-Atlantic region[2], it is dependent on the use of herbicides that are prohibited in organic production. Continuous organic no-till is widely considered unachievable[3], however there are options for reducing tillage in the mid-Atlantic region, such as: (1) rotating annual grain crops with perennial forages/pastures; (2) decreasing depth and degree of soil inversion (e.g., chisel plowing and disking in place of moldboard plow); or (3) no-till planting cash crops into cover crops that are mechanically killed with a roller–crimper. This latter approach may still require moldboard plowing prior to cover crop establishment to maintain adequate long-term perennial weed suppression, and thus is considered a rotational no-till approach. This paper focuses on the progress of research associated with cover crop-based, organic rotational no-till corn (*Zea mays* L.) and soybean (*Glycine max*) production in the mid-Atlantic region.

Interest in organic rotational no-till farming has increased substantially with the development and widespread availability of a relatively inexpensive roller–crimper for mechanically killing and flattening cover crop residue. Rollers were originally developed along with the adoption of no-tillage agriculture in Brazil and early designs in the USA were developed by USDA-ARS in Auburn, Alabama[4]. The model that is now most frequently used in the USA was popularized by the Rodale Institute (Kutztown, PA, USA). This roller–crimper is comprised of a steel cylinder (41–51 cm diameter) with metal slats welded perpendicular to the cylinder and arranged in a chevron pattern to reduce vibration. The roller–crimper has sufficient weight to kill cover crops, and can be used at a speed that is sufficient to accommodate typically sized mid-Atlantic grain farms[4,5].

Within the mid-Atlantic region, research and farmer-adoption of cover crop-based, organic rotational no-till grain systems have focused on corn and soybean production. Typically, soybean is no-till planted into a fall-planted cereal rye (*Secale cereale* L.) cover crop, whereas corn is more commonly planted into a hairy vetch (*Vicia villosa* Roth) cover crop. In both cases, the cover crop is terminated mechanically with a roller–crimper. Both of these winter annual cover crops are established in the fall in seedbeds prepared using tillage. Cereal rye and hairy vetch are common cover crops in the eastern USA,[6] because they are winter hardy and have high biomass potential and weed-suppressive potential in no-till agriculture[7,8]. Further, cereal rye has been coupled with soybeans for its residue persistence and flexible establishment date[9], while hairy vetch is coupled with corn because it can produce more than 150 kg ha^{-1} of plant available N[10].

In the mid-Atlantic region, cereal rye is sown between late August and early November and hairy vetch between late August and late September, depending on location and weather. Cash crops are no-till planted simultaneously or 7–10 days after rolling–crimping in mid-May through early June, when cover crops are flowering or in early stages of seed set, using no-till drills or planters for soybean (450,000–562,500 seeds ha^{-1}) and no-till planters for corn (75,000–87,500 seeds ha^{-1}). In general, cereal rye is rolled–crimped at an angle offset from the direction that it is sown (i.e., 30–90°) to obtain maximum soil cover by the cover crop residue and to help facilitate the soybean planting operation. The vine habit of hairy vetch precludes any specificity to the rolling direction. When rolling and cash crop planting are not performed simultaneously, planting must be done in the same direction as rolling, to avoid dragging the cover crop residue and to increase the cutting performance of the coulters.

System Performance

Collaborative research reported in this paper on the cover crop-based, organic rotational no-till system has been conducted by scientists at the USDA-ARS Sustainable Agricultural Systems Laboratory at Beltsville, MD, The Pennsylvania State University and the Rodale Institute. Corn and soybean have achieved comparable or greater yields than county averages (Table 1). However, there have been considerable annual variations in grain yield. Soybean yields have been more consistent than corn across the region. Corn performance appears to decline for the cover crop-based organic rotational no-till system in the northern area of the region, primarily due to planting delay caused by the later hairy vetch flowering. The greater overall crop performance and farmer adoption of soybean compared with corn is likely a result of the highly persistent and greater biomass levels of cereal rye residue that provides better weed suppression than does the hairy vetch residue; earlier soybean planting dates due to earlier rye maturity; greater tolerance to reduced crop stands from insect herbivory; and ability of soybean to provide its own nitrogen (N).

Still, the inability to control weeds consistently limits adoption of organic rotational no-till. In addition, perennial weed management and insect seed and seedling herbivory have constricted yields of corn and soybean. In the case of soybean, performance also has been limited by challenges associated with establishing cash crops in high levels of cover crop residue and with field variations in cereal rye biomass accumulation. In our experience with corn, the lack of consistent weed control and challenges in meeting fertility demands has greatly reduced the success of the cover crop-based production system. Finally, cover crop management for optimal performance and integration into a crop rotation represents a critical challenge to the overall success of the production system. Developing a successful cover crop-based, organic rotational no-till organic corn and soybean

Table 1. Cover crop biomass (hairy vetch/corn or cereal rye/soybean) and corn and soybean grain yield in experiments conducted by USDA-ARS, Pennsylvania State University and The Rodale Institute. Crop yields are averaged across all of the treatments and blocks of an experiment; maximum yield represents the highest treatment mean within an experiment. Standard errors are presented within parentheses.

Crop	Site	Experiment factors	Years	Cover crop mean biomass	Crop mean yield	Maximum crop yield	County average yields
				---------- Mg ha^{-1} ----------			
Corn	USDA-ARS	Crop planting date, high residue cultivation, seedbank density	2008	6.3 (0.41)	6.9 (0.29)	8.6	8.0
			2009	3.9 (0.38)	7.3 (0.51)	7.8	8.1
			2010	5.1 (0.42)	7.3 (0.35)	9.3	6.6
	Pennsylvania State University	Crop planting date, high residue cultivation, seedbank density	2008	5.6 (0.11)	5.0 (0.12)	6.6	7.8
			2009	4.1 (0.12)	4.3 (0.26)	6.9	8.6
		Crop planting date	2007	3.7 (0.20)	2.2 (0.54)	3.4	7.0
			2008	2.6 (0.06)	6.8 (0.32)	7.5	7.8
	Rodale Institute	Crop planting date	2007	NA	7.8 (0.12)	8.5	8.2
		Cropping systems; farming systems trial	2008	8.0 (0.21)	5.2 (0.17)	5.8	8.4
			2009	5.4 (0.28)	5.8 (0.77)	6.5	NA
			2010	6.5 (0.22)	5.5 (0.69)	7.5	NA
		Cropping systems	2010	5.8 (0.27)	6.2 (0.39)	6.9	NA
Soybean	USDA-ARS	High residue cultivation	2009	7.9 (0.06)	2.8 (0.09)	3.0	3.2
		Mulch rate, soybean population	2008	8.4 (0.05)	2.3 (0.04)	3.0	2.5
			2009	6.3 (0.08)	3.0 (0.03)	3.7	3.2
	Pennsylvania State University	Crop planting date, high residue cultivation	2008	7.7 (0.03)	1.1 (0.02)	1.2	2.3
			2009	7.4 (0.04)	2.6 (0.06)	3.1	2.8
		Mulch rate, soybean population	2009	8.2 (0.98)	2.3 (0.12)	4.9	2.8
	Rodale Institute	Mulch rate, soybean population	2008	10.8 (0.93)	3.2 (0.11)	3.5	2.8
		Cropping systems; farming systems trial	2009	10.8 (0.32)	2.0 (0.07)	2.3	3.6
			2010	9.5 (0.17)	1.7 (0.07)	1.9	2.7
		Cropping systems	2009	8.2 (0.79)	1.4 (0.20)	1.8	3.6

production system will require an integrated, multi-tactic approach to pest and fertility management. Our multi-institutional, multi-disciplinary team is addressing these system constraints and challenges, as discussed below.

Cover crop management: control and biomass production

The popularization of the roller–crimper for cover crop-based, organic rotational no-till grain production has created a need to research basic agronomic practices for grain production to characterize system limitations and optimize crop performance. Cover crops play a central role to the performance of these systems; therefore strategies for maximizing cover crop performance also must be evaluated. Mechanical termination of cover crops using a roller–crimper is a key component of the rotational no-till system. Our group has focused on testing the effects of termination timing on cover crop control and biomass production. While it has been known for over a decade that mechanical control of cover crops improves with increasing plant maturity[4,8], few studies have systematically defined these relationships.

Independent experiments were conducted to test the efficacy of mechanical control of cereal rye and hairy vetch across a range of cover crop phenological stages. The first experiment evaluated how cereal rye seeding date in the fall and termination date in the spring impacted mechanical control of cereal rye[5]. In this study, two cultivars of rye (Aroostook and Wheeler) were seeded at six different dates between late August and mid-October. In the following spring, the rye was rolled and planted to soybean on four different dates on a 10-day interval. Results indicate cereal rye was not consistently controlled (>85%) with the roller–crimper prior to anthesis or Zadoks growth stage 60. For the most consistent control, cereal rye should be rolled at Zadoks growth stage 65 (50% anthesis). No differences in control were observed between cultivars at any given growth stage. In another study, hairy vetch was planted at a single date in the fall and rolled at four dates on a 10-day interval once flowering had commenced. Results showed that hairy vetch control improved with each delay in the termination date and that consistent control was not achieved until early pod set[11]. A flowering index was developed to help classify hairy vetch reproduction[11].

Since hairy vetch can be vegetative, flowering and setting pods at the same time, this research focused on classifying growth stages of the first five nodes below the apical meristem or terminal branches as a bud, flower or pod[11].

In addition to the effects of timing on cover crop control, we also have tested the effects on biomass production because abundant and uniformly distributed cover crop biomass is essential for effective weed control from cover crop mulches. Growth rate and total biomass accumulation of cereal rye and hairy vetch are affected by the timing of the fall planting, spring termination date[11,12], seeding rate[13] and soil fertility[13,14]. The extent to which cereal rye tillers in the fall strongly influences its biomass accumulation potential in the spring. Delay in spring termination by 10 days can achieve comparable biomass to planting 50 days earlier in the fall, and biomass accumulation can increase 200 kg ha^{-1} day^{-1} after stem elongation. In our experience on-station and on-farm, cereal rye biomass does not typically exceed 6000 kg ha^{-1} in this region unless management is optimized in terms of seeding rate, seeding date and soil fertility, which can increase biomass up to 12,000 kg ha^{-1}.[12,13] For hairy vetch, biomass accumulation after spring green-up is 50–75 kg ha^{-1} day^{-1}.[15,16] In the mid-Atlantic region, hairy vetch biomass can be as high as 4000–6000 kg ha^{-1}.[7,11,15] However, over-yielding of total cover crop biomass can be achieved with a biculture of hairy vetch and a cereal grain relative to monocultures of these species (Fig. 1A).

Cover crop breeding/variety assessments

To fully exploit the multi-functional potential of cover crops, varietal improvements must be made. A multi-state (Maryland, New York and Pennsylvania) hairy vetch breeding program was conducted to evaluate traits of early flowering and winter hardiness. From these studies, the cold hardy, early flowering cultivar 'Purple Bounty' and 'Purple Prosperity' were developed. Both cultivars are now available in sufficient quantities for commercial use. There have been three publications linking the genetic structure of the accessions contained in the USDA *V. villosa* germplasm collection and phenotypic traits of interest to organic rotational no-till grain producers. Two of the reports link phenotypic traits to a coarse assessment of physical genome structure[17,18], while the third focuses on developing of a core genetic subset of key accessions maintained in the collection by identifying genomic markers for use in future molecular assisted breeding programs[19]. Current work is aimed at understanding the environmental and genetic controls on flowering phenology and seedbank persistence, and looking more closely at the linkages between flowering phenology, cold hardiness and N fixation.

Soil moisture

Cover crops can serve as both an asset and a liability in grain-cropping systems due to their impact on soil moisture. When winter cover crops break dormancy in spring and begin their period of rapid growth, evapotranspiration may exceed precipitation. In dry years or on draughty soils, soil moisture may be significantly depleted[20]. Systems that must delay termination until cover crop flowering for optimizing termination efficacy (e.g., roller–crimper), will also be subject to greater soil moisture removal and prone to initiating the cropping season at a soil moisture deficit. However, the roller–crimper technology that maximizes rye cover crop mortality and creates residue mulch can maximize soil moisture conservation compared with approaches that allow rye regrowth or bare soil[21].

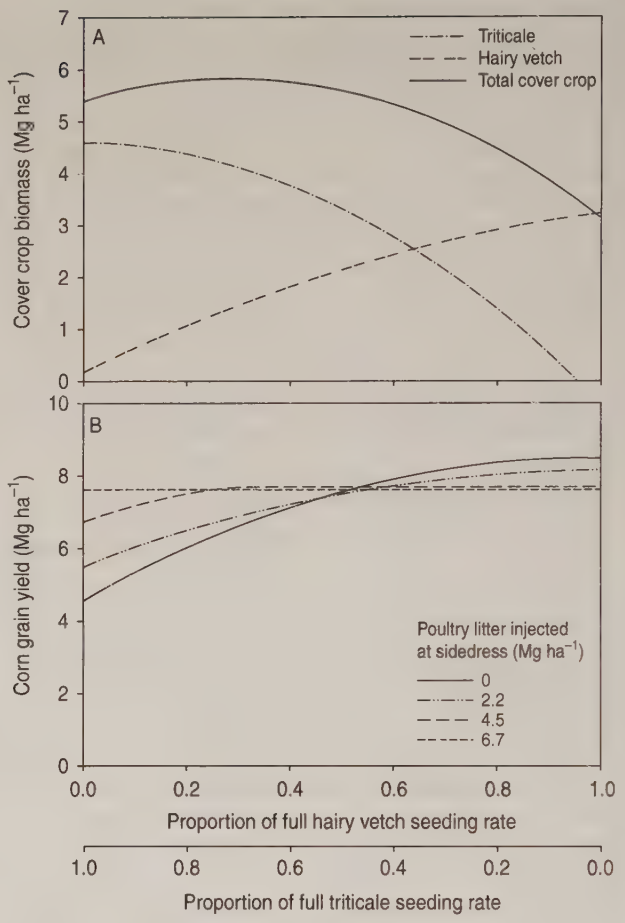

Figure 1. Cover crop biomass and corn yield as a function of hairy vetch and triticale seeding rate proportions at USDA-ARS in 2010. Full seeding rates for hairy vetch and triticale were 34 and 168 kg ha^{-1}, respectively. Cover crop biomass (A) was collected at termination and reported on a dry weight basis. Cover crop biomass response to mixture seeding rate proportion was modeled using a quadratic function. Poultry litter (B) was subsurface banded when corn was 30 cm tall (side-dress) with a prototype subsurface poultry litter applicator. Corn yields were taken from weed-free plots and reported at 15.5 g kg^{-1} moisture content. Corn yield response to cover crop mixture proportion and poultry litter rate (Mg ha^{-1}) was modeled using quadratic plateau models.

Once moisture is captured in the soil, evaporation is slowed by cover crop residue on the soil surface, with greater soil moisture retention being associated with higher residue levels[22]. Generally, diffusive resistance of water vapor through residue has been shown to be most influenced by the thickness of the residue layer[23], such that residue layer thickness is positively correlated to diffusive resistance. Research conducted in Maryland concluded that summer soil moisture conservation by cover crop residues was more important than spring moisture depletion by growing cover crops[24]. The balance between water use and conservation is influenced by local weather, soil conditions and cover crop species selection. Growers will need to weigh these offsetting effects carefully before making a final decision on the timing of cover crop management.

Crop establishment

Maximizing cover crop biomass to ensure optimal weed suppression creates high-residue environments that challenge crop seed placement. No-till planters and drills equipped with appropriate coulters, seed firmers, depth control, weight and effective closing wheels are essential for optimal crop seed placement. In rolled cover crop systems, it is necessary to cut through the fresh plant residue to create the seed slit. The coulter serves this purpose by cutting the residue and loosening the soil prior to the double disk opener. We have relied on a bubble-type coulter that is designed for residue cutting and soil penetration. Wave-type coulters are generally less desirable for cutting heavy, living residue and for penetrating drier soils due to penetration resistance. Further, aggressive wave-type coulters result in more extensive soil disruption, undermining weed suppression goals.

Heavy cereal rye mulches have been a significant obstacle to optimal soybean stand establishment. Soil moisture conditions are critical since wet soil can impair furrow closure and allow hair-pinning of rye residue. With dry conditions it is difficult to penetrate through both the rye and soil to get adequate seed placement. Cereal rye lodging, prior to planting, further constrains seed placement as the coulter must cut through residue that is lying at multiple angles. Maximizing weight on the front coulters is essential for cutting rye residue. Compared with planters, drills have more difficulty cutting through heavy rye mulches due to greater draft. In both Pennsylvania and Maryland, it was necessary to add more than 136 kg of weight above each planter row unit in order to get sufficient soil penetration under drier conditions. Residue managers (i.e., row cleaners) such as the Yetter Shark Tooth®[1] can help improve stand establishment in heavy residue. In Pennsylvania, we observed up to a 25% increase in soybean stand with the Yetter Shark Tooth residue managers compared with the same planter without residue managers (Mirsky, unpublished results). Increased populations and faster emergence time resulted in either no difference in weed biomass or up to a 70% reduction (decrease by 700 kg ha^{-1}). That said, cover crop residue can wrap around the wheels of residue managers and reduce their usefulness.

Establishing corn in rolled–crimped hairy vetch has been less difficult, but wet surface soil conditions can be common. Press wheels may not effectively close the seed furrow in wet conditions, resulting in reduced stands due to insect herbivory or poor germination resulting from seed decay and/or desiccation. Closing wheel selection and down pressure tension can minimize potential problems under high-residue situations. Spading or spiked closing wheels rather than solid types can help close the seed slit in wet soils. Site-specific evaluations of closing wheels, down pressure configurations and adjusting depth-gauge wheel settings, in different cover crop and soil moisture situations, can greatly improve stand establishment.

Insects

Growers frequently question the optimal timing of cash crop planting after rolling; there is interest in managing their cover crop and planting a cash crop in a single pass system. However, it is often recommended to wait 1–2 weeks to avoid stand losses due to diseases, insects and/or allelochemicals[25,26]. A variety of herbivorous insects attack seeds and seedlings of field crops. The principal groups are wireworms (larvae of Coleoptera: Elateridae), seedcorn maggot (*Delia platura* and related species, Diptera: Anthomyiidae) and, following seedling emergence, cutworms (Lepidoptera: Noctuidae) and related caterpillar species; these have all been observed to reduce crop populations in mid-Atlantic cover crop-based, organic rotational no-till grain systems. In conventional farming, many of these pests are suppressed by seed or furrow treatments with synthetic insecticides. In organic crop production, seed treatments are in an early stage of development, but are not anticipated to provide the level of protection available to conventional growers.

Cultural effects of tillage and cover crops on seed and seedling pests are complex, and may decrease or increase insect injury depending on species of herbivorous insects[27,28]. Early season damage to seedling corn under minimal tillage and high residue can result in heavy losses due to stand reduction[29]. Seedcorn maggot adults are attracted to areas of soil disturbance and decaying organic matter such as recently incorporated plant residues and animal manure; the larvae are more damaging under cool conditions, but populations are consistently lower in untilled systems, even those with high residue[30]. Wireworm attack on newly seeded crops is closely related

[1] Trade and company names are given for the reader's benefit and do not imply endorsement or preferential treatment of any product by the USDA, Penn State, or the Rodale Institute.

to crop history, but different genera prefer different hosts; the widespread *Melanotus* and *Conoderus* are typically worst in crops following sod or other grasses [31]. Cutworms may be favored by planting into legume cover crops and winter annuals[29,32], but their migratory habits make populations hard to predict. Armyworm [*Pseudaletia unipuncta* (Noctuidae)] damage is enhanced in killed grass, particularly cereal rye cover crops. Damage and predation differ by termination method (e.g., herbicide treatment versus mowing)[33,34], but data on roller–crimper terminated cover crops is not available. Given these species-specific phenomena, management of seed and seedling pests in organic rotational no-till grain production poses a formidable challenge.

Weed management

Surface mulches physically suppress weeds by altering light quantity and quality, temperature at the soil surface, and by acting as a barrier to reduce seedling emergence[22]. Quantity of residue is more important than the type of residue and weed suppression is less affected by allelopathic than by physical properties of mulches[35]. Previous research showed that cover crops or other organic mulches must be present in high amounts to provide a high level of physical suppression of annual weeds, whereas levels below 2200 kg ha^{-1} can stimulate weed emergence[36,37] by reducing surface soil water evaporation. In New York and Maryland, greater than 75% inhibition of summer annual weed emergence was consistently achieved when mulch biomass exceeded 8000 kg ha^{-1} and mulch thickness exceeded 10 cm[35].

The effect of cover crop residues on weed control is species-specific[36,38] and is the result of: (1) variation in temporal synchrony between weed germination and the presence of a sufficient quantity of cover crop biomass to influence that process; and (2) the energy reserves of a given weed species (i.e., large seed versus small seeded; perennial versus annual). In general, cover crop mulches are better at suppressing small-seeded summer annuals and are largely ineffective at suppressing perennial weeds. Reducing tillage typically results in a shift from annual to perennial weeds; this weed community shift was observed in Rodale Institute's long-term cropping systems experiment[39]. Clearly, perennial weeds can become problematic in organic no-till planted crops, and illustrate the need for low perennial weed populations in fields where the cover crop-based, organic rotational no-till approach is implemented.

High-residue cultivators have been developed to kill weed seedlings between crop rows with minimal disruption of residue on the soil surface[6]. New residue management equipment integrated with traditional high-residue cultivators are now available that minimize soil disturbance to a depth of 2–5 cm. Such cultivators use press wheels with coulters to facilitate slicing through the residue along with wide, flat sweeps that pass underneath the cover crop residue to cut the weeds off beneath the soil surface. Research in Maryland and Pennsylvania demonstrated that this type of high-residue cultivator decreased weed biomass by 66 and 52% and increased yield 23 and 61% in organic no-tillage soybean and corn, respectively, compared with mulch alone.

Effective weed control in organic rotational no-till grains production requires integration of cover crops and high-residue cultivation into a weed management program that includes additional management tactics[37]. Cultural weed management tactics within the cover crop-based corn and soybean systems that we have evaluated include crop seeding rate[37], timing of cover crop management[12], cover crop seeding rate[13] and cover crop mixtures[12,40]. Effective weed control in these systems demonstrates the need for an integrated approach, exploiting multiple stress and mortality factors (i.e., many little hammers)[41]. A comprehensive approach to develop cover crop-based multi-tactical weed management systems first requires defining the functional relationship of a management tactic on weed response. Subsequent efforts should include developing an understanding of how all tactics interact (synergism versus antagonism) to maximize weed suppression and minimize adverse crop effects.

Soil fertility

Cover crop-based organic rotational no-till will require soil fertility-management strategies that meet the agronomic needs of the crop, while reducing weed competitiveness. For example, decomposition of cereal rye mulch immobilizes soil N near the soil surface that can suppress weed germination and growth[42]. Hairy vetch can provide substantial levels of N to the subsequent corn crop; however, the residue provides inferior season-long weed suppression unless combined with a cereal[40]. Using a cereal/legume mixture may increase weed suppression compared to a legume monoculture, but such mixtures often reduce the release rate and total available N from the legume[43]. While adequate and well-synchronized N fertility is essential to optimize both yield and quality of corn[44], excessive application of N fertility sources is costly, has significant environmental ramifications[45] and can increase weed competition. No-till management[46] and manipulation of supplemental soil fertilizer placement (e.g., subsurface banded next to the crop row) and timing are viable options for improving crop N uptake and influencing weed–crop competition relationships[47]. Preliminary work in Maryland demonstrated an approach to integrating fertility management with both animal (poultry litter applicator prototype)[48] and green manures (Fig. 1B). Cover crop biomass was maximized at a relatively low vetch proportion of $\approx$30%, while corn yield could be maintained across cover crop mixture proportions by subsurface banded poultry litter at 4.5–6.7 kg ha^{-1}. Such multi-tactical strategies for

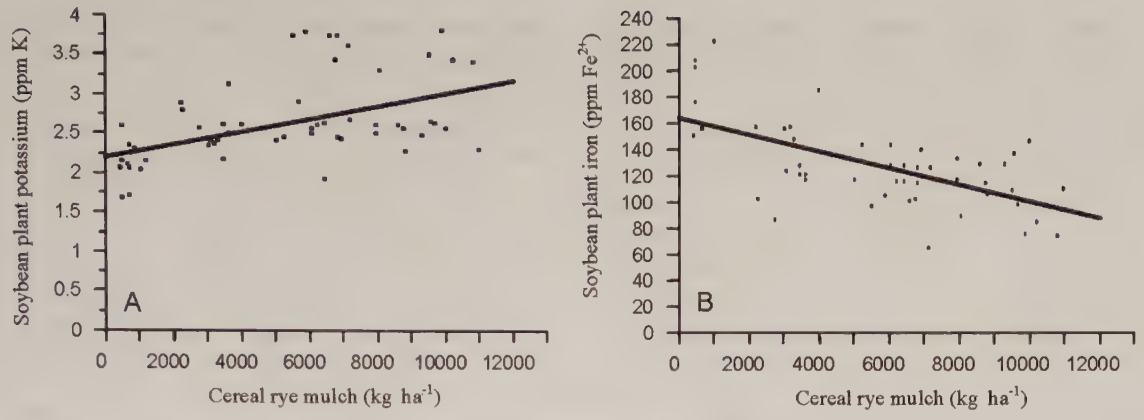

Figure 2. Impact of cereal rye mulch rate on mineral content of soybean plants at USDA-ARS in 2008–2009: (A) plant potassium concentration and (B) plant iron concentration.

maximizing weed suppression through optimal cover crop mulch and corn N management provide new opportunities for increasing the consistency of corn performance in an organic rotational tillage environment.

Cover crop residues on the soil surface can have both direct and indirect effects on biogeochemical processes[49]. For example, a dose-dependent effect of rye mulch biomass on soybean plant iron concentration and potassium concentration was observed in Maryland (Fig. 2). It is unclear with currently available data how other leachates from rye mulch, such as dissolved organic C, might impact the soil microbial community in regard to soil N immobilization and plant microbe interactions. For example Bending *et al.*[50] showed that crop residue from a variety of plant species can differentially influence soil microbial metabolic functionality. The legacy of different crop residues has been shown to drive shifts in microbial community structure[51]. Mechanisms underlying these observations are still unidentified but an active area of on-going research.

Global Warming Potential, Energy Use and Labor Requirements

Currently, there are federal and state monetary incentive programs[52] to help farmers implement practices that enhance the multi-functionality of agroecosystems for the production of non-market ecosystem services (i.e., soil, water and air quality)[53]. To increase agricultural sustainability, research should focus on the development of systems that sequester soil C, decrease soil and nutrient loss through surface runoff and leaching, reduce external inputs and increase system resilience. While there are challenges associated with cover crop-based organic rotational no-till, there are clear indications that such production practices may meet the needs of a new multi-functional agriculture. Cover crop-based organic rotational no-till may increase C sequestration by increasing the rate and magnitude of cover crop biomass production, adding an external source of C to soil (e.g., manure or compost) and/or eliminating tillage[54,55]. In the southeastern USA, no-till management of cropping systems that included cover crops sequestered $0.53\,Mg\,C\,ha^{-1}\,yr^{-1}$, while no-till systems without cover crops sequestered only $0.28\,Mg\,C\,ha^{-1}\,yr^{-1}$ (93 unpaired observations)[56].

In contrast to no-till, organic cropping systems rely heavily on tillage, but have been reported to share some of the same benefits of no-till systems, including a lower net C flux. Despite the high frequency of tillage commonly implemented in organic systems, results from a long-term experiment in Maryland showed greater soil C sequestration rates in organic compared to a conventionally managed no-till system regardless of whether or not cover crops were used in the no-till system[57]. Thus, organic rotational no-till crop production with its reliance on high cover crop biomass production has strong potential to sequester soil C.

In addition to the potential to increase soil C sequestration, cover crop-based organic rotational no-till grain systems could greatly reduce energy requirements and GHG emissions through fewer tractor operations, among organic systems, and shift in fertilizer from mineral to organic when comparing organic to conventional systems that rely solely on mineral fertilizers. The Farm Energy Analysis Tool (FEAT), a static deterministic model parameterized with data from a comprehensive literature review[58], was used to quantify the impact of tillage on energy use and GHG emissions on a simulated 'average' Pennsylvania grain production farm (154 ha in size). Using FEAT, a hypothetical corn–soybean–wheat rotation was evaluated using (1) standard organic and (2) cover crop-based organic rotational no-till management, compared to (3) a perennial organic system that included corn–soybean–wheat plus 2 years of a hay crop. The systems differed in the use of tillage, soil fertility management, weed control and seeding rates (Table 2). The boundary was restricted to the farm gate and included only farm operations and critical soil processes associated with N (fixation and denitrification). Inputs included labor, soil amendments, crop seed, diesel fuel and

Table 2. Tillage, fertility management and weed control in three simulated cropping systems. Systems include a corn–soybean–wheat crop rotation under standard organic and organic rotational no-till management, and a 5-year corn-soybean–wheat–red clover hay rotation using standard organic management.

System	Tillage	Cover crops	Soil fertility	Weed control
Organic	Moldboard plow, disc and cultipack before crops	Hairy vetch plowed at 3 Mg ha^{-1} before corn; rye plowed at 5 Mg ha^{-1} before soybean	Manure (11,850 l ha^{-1}) before corn (112 kg N ha^{-1} from hairy vetch); manure (21,600 l ha^{-1}) before wheat	Rotary hoe (2×), and inter-row cultivation (3×) for corn and soybean
Rotational no-till	Moldboard plow, disc and cultipack before cover crops and small grains	Hairy vetch rolled at 5 Mg ha^{-1} at corn planting; rye rolled at 10 Mg ha^{-1} at soybean planting	Manure (20,324 l ha^{-1}) before wheat [hairy vetch provides N (134 kg ha^{-1}) for corn]	Mulch from cover crop residue in corn and soybean
Perennial	Moldboard plow, disc and cultipack before crops; no-till rye	Rye plowed at 5 Mg ha^{-1} before soybean	Manure (20,325 l ha^{-1}) before corn (89 kg N ha^{-1} from red clover); manure (21,600 l ha^{-1}) before wheat	Rotary hoe (2×), and inter-row cultivation (3×) for corn and soybean

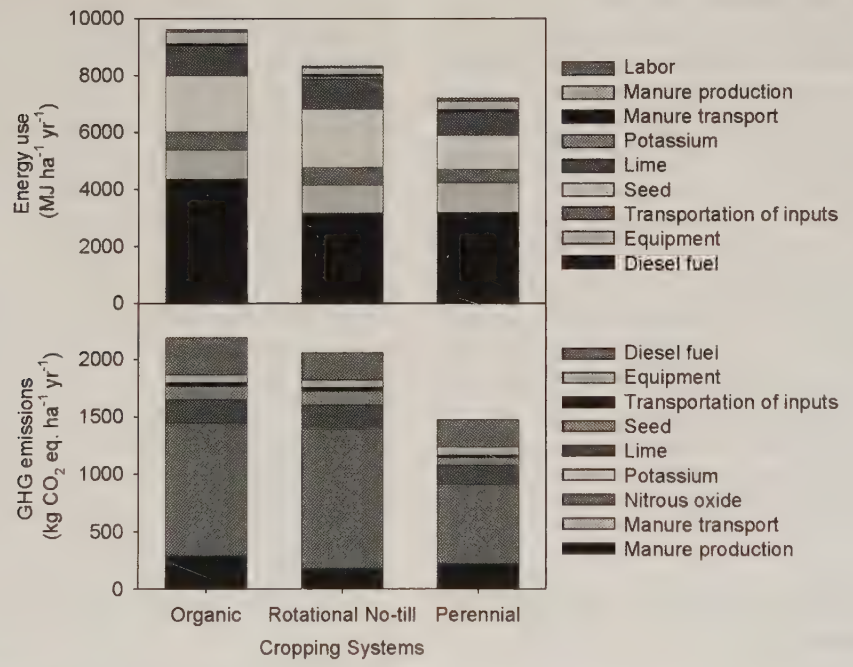

Figure 3. Energy usage and GHGs annualized over a corn–soybean–wheat crop rotation under standard organic and organic rotational no-till management, and a 5-year corn–soybean -wheat–red clover hay rotation using standard organic management.

equipment. Outputs included grain yield, energy use and GHG emissions. In the GHG analysis, N lost from the system as N_2O was included. Soil N_2O emissions were estimated based on the amount of N supplied (1% N_2O/N from plant residue sources and 2% N_2O/N-input for N applied with manure) and converted to CO_2 equivalents[59].

Reducing tillage in organic production resulted in an estimated decrease in energy use and GHG emissions (Fig. 3). Annual energy use in the cover crop-based organic rotational no-till system was lower than in the standard organic system, largely due to reduced diesel fuel and labor needs. Nitrous oxide was responsible for the relatively large GHG emissions in the standard organic and cover crop-based organic rotational no-till systems. Although the lowest energy use and GHG emissions were in the perennial system, this system did not produce grain in 2 of the 5 years. Therefore, the cover crop-based organic rotational no-till system could increase energy efficiency, reduce GHG emissions and be economically more sustainable than current tillage-based organic systems.

Conclusions

Success of a cover crop-based organic rotational no-till grain production system is going to be contingent on five

management factors: (1) consistent and optimal performance of selected cover crops; (2) maintenance of low perennial and annual weed populations; (3) advances in manure placement technology; (4) innovations in organic protection of crop seed and seedlings; and (5) continued advances in crop seed placement equipment. Despite the challenges, it is clear that there are very good reasons for investing resources in the development of the organic rotational no-till system. Reducing energy use and GHG emissions in a way that maintains productivity coupled with farmer interest in saving time will continue to drive innovations that are needed to increase the performance and consistency of cover crop-based organic rotational no-till.

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Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA

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Abstract

Organic systems in the southeastern USA offer unique challenges and solutions to crop production due to regional soil and climate characterized by highly weathered soil types, high precipitation and the capacity to grow cover crops in the winter. Recently, the interest of producers and researchers in high-residue cover crops and conservation tillage systems has increased. Various designs of the roller–crimper to manage cover crops have been invented and demonstrated to growers in the southeastern region of the USA over the past 17 years. The impacts of high-residue cover crop mulches on the agronomic systems in the region are diverse. Legume cover crops assist with meeting N demand from cash crops though they decompose rapidly and are seldom sufficient for N demanding crops such as corn. Cereal cover crop mulches can have the opposite effect by immobilizing N and have a longer impact on soil moisture and weed dynamics. While undesirable for many crops, N immobilization is one possible mechanism for weed suppression in legume cash crops planted into cereal residues. Other cover crop weed suppression mechanisms include physical impedance, light availability, allelopathy and microclimate effects. Regardless of the cause, successful weed control by mulches is highly dependent on having substantial biomass. The southeastern region is capable of producing cover crop biomass in excess of 9000 kg ha^{-1}, which is sufficient for weed control in many cash crops, although supplementary weed control is sometimes necessary. Long-term data are needed to predict when farmers should add supplementary weed control. More work is also needed on how much additional N is required for the cash crops and how best to deliver that N in a high-residue environment using organic sources.

Key words: roller–crimper, organic, no-till

Roller–Crimpers and Terminating Cover Crops

Rolled cover crops have been a primary research focus as a means to increase cover crop adoption and reduce tillage on organic farms in the southeastern USA. Rolling technology originated in Brazil where producers have been using rollers successfully for decades in no-till conservation systems[1]. The Brazilian-type roller/crimper design (Fig. 1a) did not result in wide adoption in the USA in part due to vibration transferred to the tractor and operator as speed increased. To increase adoption, research has been conducted by the USDA-ARS National Soil Dynamics Laboratory since 1994 on new roller designs that are effective in terminating cover crop, but generate less vibration (Fig. 1b, c). Based on the success of the novel roller designs, new concepts for rollers/crimpers intended for vegetable production were developed, such as an elevated bed roller to terminate cover crops on row-tops and in furrows (Fig. 2).

Both general principles and soil-type-dependent practices are needed for establishing cash crops in thick cover crop mulches. One general principle is the need to roll–crimp cover crops parallel to the cash crop planting direction because it minimizes or eliminates residue buildup on subsoiling and planting units. Previous research has documented that diagonal and perpendicular rolling directions will cause residue buildup, increase cleaning time of planting units from residue and decrease planting quality, i.e., skips in planting, 'hair pinning' and slow emergence[2]. In addition, row cleaners mounted immediately prior to or after the cutting coulter (Fig. 3) can further enhance direct seeding and transplanting operations.

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Figure 1. Different roller types: (a) original Brazilian type straight bar roller, (b) curved bar roller–crimper and (c) smooth roller with crimping bar (U.S. patent no. 7,604,067 B1).

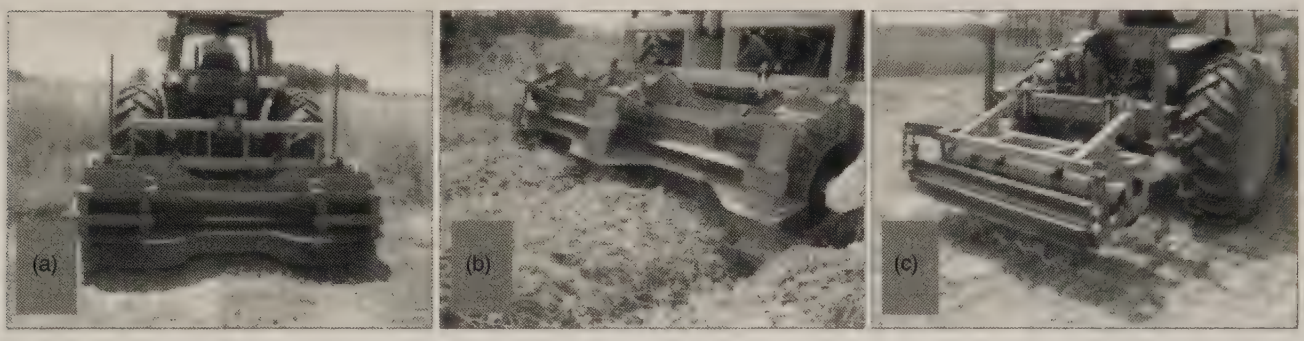

Figure 2. (a) Roller–crimper for elevated beds: one row and two furrows. (b) Roller for elevated beds: two rows and three furrows. (c) Two-stage roller/crimper designed to operate with smaller tractors (40 HP power source). The roller comprises a 30 cm diameter smooth drum which rolls down the cover crop and second small 15 cm diameter drum with six equally spaced 0.6 cm-thick crimping bars on the drum's perimeter. Depending on cover crop type and amount, crimping force can be adjusted by changing preloading force of two adjusting springs to obtain the best crimping characteristics for a particular cover crop. Patent pending—U.S. Patent no. 7,562,517 B1.

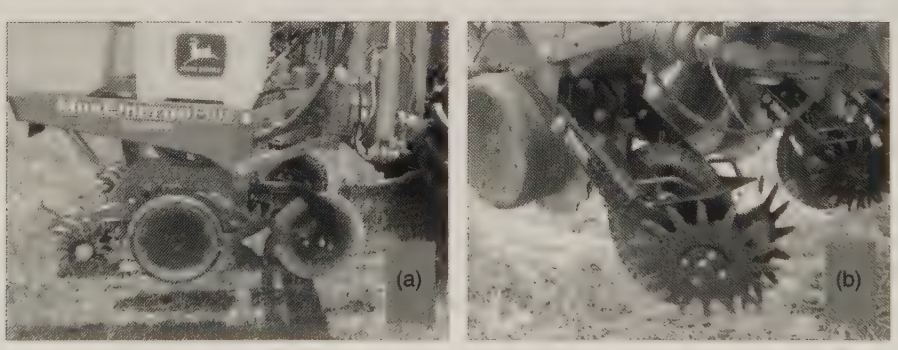

Figure 3. (a) John Deere no-till planter for planting cotton seeds into rye residue cover using DAWN™ row cleaners and (b) John Deere no-till planter with attached Yetter™ row cleaners.

Rollers have been shown to be beneficial by flattening the cover crop to provide a mat over the surface of the field and prevent multiple-direction lodging of cereal cover crops[3]. Effectively killing cover crops without herbicides depends on the growth stage and species involved. The best growth stage for terminating cereal rye is from early milk to soft dough[4], late flowering for crimson clover[5] (*Trifolium incarnatum* L.) and when pods are first seen in the upper five nodes of hairy vetch[6] (*Vicia villosa* Roth). Rye is typically greater than 90% terminated after 3 weeks if rolling is performed at the optimal stage[4,7,8]. Cover crops should be terminated 2–3 weeks prior to planting to restore soil moisture depleted by the cover crop[9–11].

Weed Management Impacts of Reducing Tillage

For growers transitioning to and maintaining organic production, identifying effective weed control strategies

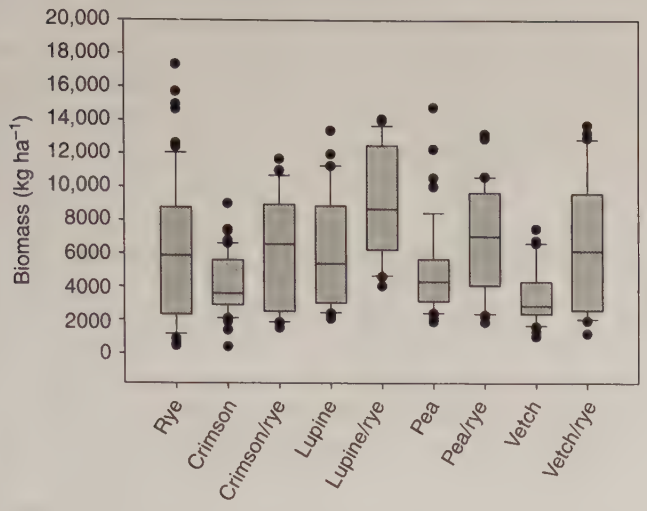

Figure 4. Productivity of legumes and legume/cereal mixes in the Southeast from 2008 to 2010. Figures come from a pooled analysis of trials in Georgia (GA) and North Carolina (NC). Box plots were created from nine site-years for all cover crops except for lupine and lupine/rye, with four to six replicates per site-year. Lupine data are from GA only (five site-years) due to extremely low productivity in NC. Crimson clover varieties: *T. incarnatum* L. 'AU Sunrise' in NC; 'Dixie' in GA. Vetch varieties: *V. villosa* Roth 'AU Early Cover' in NC; *V. sativa* L. 'Cahaba White' in GA. Winter pea varieties: *P. sativum* L. subsp. *sativum* var. *arvense* (L.) Poir 'variety unstated' in NC and GA. Narrow-leaf lupine varieties: *L. angustifolius* L. 'TifBlue 78' in NC and GA. NC data adapted from Parr et al.[5]. Rye (*Secale cereale* L.) at both locations was 'Wrens abruzzi' grown without added N fertility.

can be the most problematic issue faced[12–15]. As with conventional systems, adequate weed control is crucial for achieving optimal yields in organic systems. Traditionally, organic producers have primarily relied upon mechanical methods to maintain sufficient weed control due to the lack of synthetic herbicide options[16]. Whether through initial tillage, in-season cultivation, hand removal of weeds or flaming, mechanical means to inhibit weed growth are very effective tools for reducing weed pressure in organic systems[16,17]. However, these practices degrade soil quality, require more labor, necessitate multiple field passes or may not fully control certain weed species. Several mechanical control tactics such as rotary hoeing or flex-tine harrowing can only destroy weeds at very early growth stages[18]. Extensive cultivation with implements such as the rotary hoe can also damage crops[19]. Weather conditions, such as prolonged periods of precipitation, can also complicate mechanical control by delaying cultivation and allowing weeds to reach a growth stage that precludes effective control. Moreover, continuous tillage practices can increase soil erosion through water runoff in an agricultural system. Organic growers need additional weed control methods that are less time sensitive, less labor intensive and that enhance soil conservation and soil quality.

Mechanisms of weed control by mulches

Cover crops can stress weeds at multiple points in their life cycle, including reducing seedling establishment, minimizing growth and competitive ability and reducing or preventing production of propagules[20]. Emergence of small-seeded annual weeds is reduced with increasing rates of mulch residue[21–23]. Some of the troublesome small-seeded broadleaf weeds common to the southeastern region include Palmer amaranth (*Amaranthus palmeri* S. Wats.), spiny amaranth (*Amaranthus spinosus* L.) and redroot pigweed[24,25] (*Amaranthus retroflexus* L.). Physical impedance and light availability are important factors influencing weed establishment, especially with small-seeded weeds[23,26,27], though other factors likely contribute to weed suppression, including allelopathy[22,28–30] and microclimate effects[31]. Nitrogen immobilization may also be playing a role in soybean/rye systems because low N conditions can favor growth of N-fixing crops over non-N fixing weeds[32].

Cover crop productivity impacts on weed management

Hairy vetch produced 2340 kg ha^{-1} of dry biomass in Mississippi, but had little effect on reducing densities of smooth pigweed[33] (*Amaranthus hybridus* L.). This level of biomass residue was likely insufficient to suppress weeds and likely degraded rapidly. In the northeastern USA, weed densities were reduced with cover crop residues between 6000 and 8500 kg ha^{-1}, double the amount of documented growth in that region[21] (plots were supplemented with additional residues). Legume monocultures generally do not achieve that level of productivity in the southeastern USA[34] (Fig. 4). However, rye/legume mixes can produce significantly more biomass than legume monocultures (Fig. 4). Rye monocultures produce more biomass than other cover crops in Alabama[35], Georgia[36] and North Carolina[34]. Narrowleaf lupin (*Lupinus angustifolius* L.) is the only other winter cover crop that can reach biomass levels similar to rye but its sensitivity to frost damage limits its usefulness to the most southern parts of the region (Fig. 4). Mixtures of rye with winter legumes have shown increased weed suppression compared to winter legumes alone in Arkansas and may extend weed suppression benefits, as legume residues decompose more rapidly than rye[37].

Traditionally, rye cover crops in the southeastern US are planted at relatively low seeding rates (60 kg ha^{-1}) in late autumn, with minimal inputs, and are mowed prior to planting the summer crop. To maximize the weed control provided by a rye mulch, a more intensive cover crop management system is needed. Planting early, with higher seeding rates and adequate N fertility,[7,38] is needed to maximize the amount of rye biomass. Appropriate cultivar selection, long an under-studied component of cover crop systems, can also contribute to biomass

Table 1. Earliest roll times and productivity for rye (*Secale cereale* L.) cover crops in North Carolina. Rye was grown with 90lb N applied to simulate maximal potential rye growth for each location.[1]

Maturity	Estimated roll time[2]	Cultivar	Biomass[3]
			($kg ha^{-1}$)
Early	Late April	Wrens Abruzzi	11,500 a[4]
		Maton II	11,300 ab
		Wrens 96	10,800 ab
Mid	Early May	Aroostook	10,300 ab
Late	Mid to late May	Wheeler	10,200 b
		Rymin	8600 c

[1] Adapted from Wells et al.[62]
[2] Estimate based on average time each cultivar reached Feeke's stage 11.1 (milk).
[3] Biomass values are averaged over three site-years in North Carolina.
[4] Means followed by the same letter are not significantly different according to Fisher's Protected LSD.

production and affect the timing of the system (Table 1). While intensive management for a cover crop is uncommon, the potential economic value from improved weed control and higher crop yields would justify such investments. Relative to multiple spring tillage passes and repeated cultivations of the cash crop, more intensive cover crop management can be economically beneficial by comparison[6,39]. With adequate fertility, rye biomass yields can exceed $9000 kg ha^{-1}$; a level of biomass that affords excellent weed control[21,40] (Fig. 5). However, substantial year-to-year variation in biomass production suggests that supplementary weed control will be necessary in some years.

Supplementary weed control

Supplemental weed control options are limited when utilizing high-residue cover crop mulches. Most cultivators will not work in such a high-residue environment. One type of cultivator that is reportedly successful on a variety of soil types is the wide sweep cultivator mounted on a parallel linkage[40,41]. Most models consist of a large, smooth coulter mounted ahead of a wide sweep cultivator that has one or two depth wheels located near each sweep. The angle of the sweep relative to the soil surface is generally adjustable. Running the cultivator completely flat, or parallel to the soil surface, severs weed root systems minimally disturbing residue and soil. However, rerooting is possible with wet conditions, particularly with smaller weeds.

Herbicide options are limited in number and efficacy in organic systems[42,43]. Available herbicides used in the southeastern USA largely contain either clove oil or citric acid and are non-selective in nature[16]. In addition to being costly, previous research has shown that these natural herbicides can be inefficient weed control methods[43]. Under-leaf band spraying of nonselective herbicides would fit well into mulch systems, but the high cost and only partial effectiveness make them economically infeasible for corn and soybeans, though they may have a role in higher-value crops.

Fertility impacts of rolled cover crops

In the Southeast, the ideal time for successful roll kill of cover crops often occurs late in the spring and is not ideal for timely corn planting[6,44,45]. It is now well understood that rolled termination of cover crops is most effective after plant anthesis[4]. Susceptibility of legume cover crops to rolling has been shown to be significantly later than the traditional termination time for incorporated legumes, with rolling occurring in late-April for crimson clover varieties, mid-May for hairy vetch varieties and winter peas (*Pisum sativum* L. subsp. *sativum* var. *arvense* (L.)), and late-May for common vetch (*Vicia sativa* L.) and berseem clover (*Trifolium alexandrinum* L.)[5]. While late termination can delay corn planting, it can also result in significant increases in legume biomass N returned to the system due to having a longer period of time for spring growth and N accumulation[46–48]. Hairy vetch and crimson clover have been shown to average 4900 and $5500 kg ha^{-1}$, respectively, in North Carolina[5], resulting in 150 and $120 kg N ha^{-1}$. A strong positive correlation has been found between the number of growing-degree days and vetch biomass production[46], meaning that year-to-year variation in vetch production can be significant depending on planting date and winter temperatures.

Nitrogen mineralization from legume cover crops

Nitrogen delivery in rolled cover crop legume systems can differ significantly from green manure systems in which the cover crop is incorporated into the soil[49]. In particular, microbial function is affected by the change in plant quality that results from delayed termination, and by the change in decomposition kinetics due to the position of the rolled surface mulch in relation to soil decomposers.

The biologically driven, thus often delayed, termination time necessary in rolled systems is the first constraint that can potentially impact mineralization rate. As rolled cover crops are only successfully terminated at anthesis, plant quality and chemistry are expected to be distinctly different from earlier termination with herbicides. Decomposition and mineralization are microbial processes controlled in part by plant chemistry determinants. Such indicators include tissue C:N ratio, and cellulose, hemicelluloses, lignin and phenolic content. Ratios of C:N below 25 are assumed to release N soon after termination, but N mineralization slows with increasing hemicellulose, lignin and phenolic content, regardless of C:N ratio[50,51]. Hairy vetch residue, having been found to have low

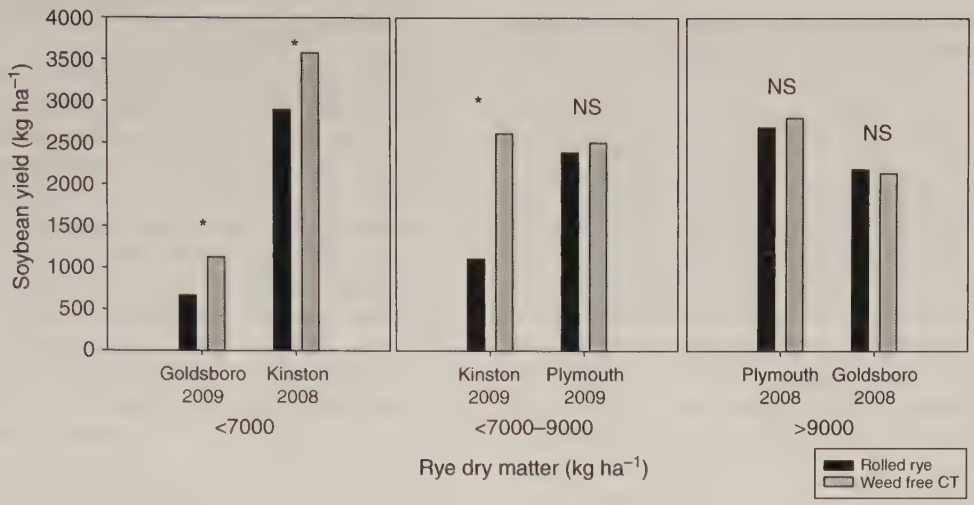

Figure 5. Soybean yield in roll-crimped rye mulches. Treatments consisted of rolled rye mulch with no additional weed control measures (rolled rye) and a weed-free, conventionally tilled check treated with S-metoloachlor pre-emergence, imazethpyr post-emergence and hand weeding as needed. Adapted from Smith et al.[39].

hemicellulose concentrations and a C:N ratio of around 11, is known to release N faster than other residues in chemically terminated systems[50]. In rolled systems, C:N ratio has been shown to increase with later roll dates as plants age, with the lowest ratios in hairy vetch and winter pea varieties observed to range from 11 to 15:1 and crimson clover from 17 to 20:1[5]. Despite the relatively narrow gap in C:N ratios between crimson clover and hairy vetch, N release can be substantially slower from crimson clover[52].

The second constraint in rolled systems that could impact mineralization is the placement of the cover crop residue in relation to the decomposing soil microorganisms. Cover crop termination in organic systems is mechanical, often involving a combination of methods that may include tilling, mowing, undercutting and rolling/crimping; each differently affecting the ability of soil microorganisms to decompose and release biomass N. In general, residue incorporation buries plant tissue, placing it in close contact with decomposing soil microbes, and increases rate of decomposition and N release, which may lead to a lack of crop-N synchrony as N is released faster than crops can use it[53]. Mowing or chopping residues increases residue surface area available to soil decomposers, increasing decomposition and reducing the overall biomass bulk[54,55]. Previous work on no-till cover crop residues relying on chemical desiccation to terminate crops has been shown to increase N mineralization compared to untreated residues[54]. Rolled cropping systems in the Southeast in particular provide a unique environment for cover crop residue decomposition. While the increased temperatures and moisture of southern climates may be favorable and hasten decomposition[56,57], the amount of soil-to-residue contact in rolled systems can also affect decomposition[55], with position on the soil surface of rolled residue altering microbial access to residue and slowing N mineralization. Further, while surface residues can conserve soil water and prevent evaporation from the soil surface prior to canopy closure[58], the exposed nature of surface mulches may slow decomposition as a result of reduced water content in the residue. Data on controls of N release in rolled cover crop legumes are scarce, and this is a topic that should be investigated further. Peak extractable soil N under rolled hairy vetch has been observed to occur at 4 weeks after termination, slower than is typical for incorporated residues in the region, but still earlier than peak N demand by corn[52]. Vetch/grass mixtures contain approximately the same amount of N as vetch monocultures, but mixtures can often release N more slowly[50]. Among legume species, variation in N release rates can be agronomically important. When terminated at anthesis, crimson clover release rates are notably slower than other legumes[50] and have even resulted in apparent net immobilization in rolled systems[52].

Future directions

Information on how high-residue systems are impacting on insect and disease management is mostly missing from southeast organic systems. One exception is a variety of studies in the Appalachian region on organic vegetable production with reduced tillage[59–61], but equivalent work is missing in field crops. Anecdotally, three-cornered alfalfa hopper damage has been observed to be higher on soybeans in rolled rye in multiple states (Reberg-Horton, personal communication). While weed management has been a central area of inquiry in multiple states, long-term data on how these systems shift weed species composition are also lacking. A complete abandonment of tillage in organics is likely impossible, but the question of how

much tillage can be removed from these systems without selecting for perennial weeds will require longer-term trials.

The next stage of organic research also needs to fine tune agronomic recommendations for growers. By all appearances, legume cover crop mulches should not be the sole source of N fertility for corn (Fig. 4). Methods and rates of supplementation need to be investigated. The combination of heavy residue and bulky organic amendments make these lines of work a nontrivial task. Another open question lies in how reliably cover crop mulches can provide enough residue to suppress weeds. Clearly, some winters are not conducive enough to cover crop growth for sufficient biomass. Farmers need tools to predict when biomass is insufficient so they can utilize off-field mulch amendments or a clean-till system instead. Ideally, models could assess cover crop biomass potential in the early spring when changing to a clean-till system is relatively easy. By late spring, even poor cover crop stands can be difficult to incorporate well enough to facilitate conventional cultivation.

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Organic no-tillage system effects on soybean, corn and irrigated tomato production and economic performance in Iowa, USA

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Abstract

Novel technologies to reduce tillage in organic systems include a no-tillage roller/crimper for terminating cover crops prior to commercial crop planting. The objective of this experiment was to compare: (1) weed management and yield effects of organic tilled and no-tillage systems for corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.] and irrigated tomato (*Lycopersicon esculentum* Mill.), using a roller/crimper and two cover crop combinations [hairy vetch/rye (*Vicia villosa* Roth/*Secale cereale* L.) and winter wheat/Austrian winter pea (*Triticum vulgare* L./*Pisum sativum* L. ssp. *arvense* (L.) Poir.)]; and (2) the economic performance of each system. Weed management ranged from fair to excellent in the organic no-tillage system for soybean and tomato crops, with the rye/hairy vetch mulch generally providing the most weed suppression. Corn suffered from low rainfall, competition from weeds and hairy vetch re-growth and, potentially, low soil nitrogen (N) from lack of supplemental fertilization and N immobilization during cover crop decomposition. No-tillage corn yields averaged 5618 and 634 kg ha^{-1} in 2006 and 2007, respectively, which was 42–92% lower than tilled corn. No-tillage soybeans in 2007 averaged 2793 kg ha^{-1} compared to 3170 kg ha^{-1} for tilled soybeans, although no-tillage yields were 48% of tilled yields in the dry year of 2006. Irrigated tomato yields averaged 40 t ha^{-1} in 2006 and 63 t ha^{-1} in 2007, with no statistical differences among tillage treatments. Economic analysis for the three crops revealed additional cover crop seed and management costs in the no-tillage system. Average organic corn returns to management were US$1028 and US$2466 ha^{-1} greater in the tilled system compared to the no-tillage system in 2006 and 2007, respectively, which resulted mainly from the dramatically lower no-tillage yields. No-tillage soybean returns to management were negative in 2006, averaging US$ −14 ha^{-1}, compared to US$742 ha^{-1} for tilled soybeans. However, in 2007, no-tillage soybean returns averaged US$1096 ha^{-1}. The 2007 no-tillage irrigated tomato returns to management averaged US$53,515 compared to US$55,515 in the tilled system. Overall, the organic no-tillage soybean and irrigated tomato system demonstrated some promise for reducing tillage in organic systems, but until economic benefits from soil carbon enhancement can be included for no-tillage systems, soil improvements probably cannot offset the economic losses in no-tillage systems. Irrigation could improve the performance of the no-tillage system in dry years, especially if grain crops are rotated with a high-value irrigated tomato crop.

Key words: cover crops, organic weed management, roller/crimper, hairy vetch, rye

Introduction

In the most recent (2008) US Department of Agriculture (USDA) statistics on organic agriculture, land under certified organic production increased to 1.9 million ha[1], with 78,767 ha of organic corn (*Zea mays* L.), 50,837 ha of organic soybean [*Glycine max* (L.) Merr.] and 66,380 ha of organic vegetable crops. Consumer demand continues to drive the organic industry due to individual preferences for lower pesticide residues in food[2] and consistent federal standards for products marketed as 'organic'[3]. At the heart of organic regulations is the protection or

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enhancement of carbon (C) and other nutrients in soil organic matter, which maintains soil fertility and soil structure in sustainable systems[4]. In order to enter the expanding organic market and meet certified organic requirements, producers must implement a soil-building plan in accordance with sections 205.203 and 205.205 of the USDA National Organic Program (NOP), Agriculture Marketing Service[3]. Although weeds in organic systems are managed through a multi-pronged approach that includes cultural, biological and mechanical methods, currently, organic producers primarily rely on C-intensive tillage systems for weed management and field preparation. Increased use of strategies that enhance or sequester soil C on organic farms, such as reduced or no-tillage systems, will lead to decreased erosion and facilitate participation in government programs supporting reductions in C emissions. Some of the most critical needs of transitioning and certified organic growers are methods for enhancing soil fertility and managing weeds[5,6]. The potentially negative effects of mechanical tillage on soil C can be mitigated by C additions from crop residues, cover crops and compost[7], but organic farmers also have expressed interest in reducing tillage operations[8]. Although plastic mulch is allowed in certified organic vegetable systems for weed management, many organic and conventional vegetable farmers are seeking alternatives to plastic mulch, which is expensive, difficult to dispose of and may have negative impacts on soil microbial activity[9]. Natural mulches, including crushed and desiccated cover crops, have been proposed as an option in organic weed management. The most common cover crops planted in organic systems have included single species or combinations of rye (*Secale cereale* L.), barley (*Hordeum vulgare* L.), wheat (*Triticum vulgare* L.), hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.), due to their quick establishment, ability to over-winter, competitiveness with weeds and ease of termination using mechanical methods[10,11]. The cover crop combination of winter rye and hairy vetch offers great potential for enhancing crop yields and soil quality. Benefits ascribed to winter rye include C acquisition through biomass accumulation, residual soil nitrogen (N) scavenging and reduced nitrate leaching[12,13]. In addition, increased weed management from rye cover crops can be obtained through physical interference, antagonism and allelopathy[14,15]. Hairy vetch is considered an excellent cover crop in terms of biomass production, providing some degree of weed suppression and N supplementation up to 138 kg $N\,ha^{-1}$ [16–18].

Cover crop termination methods utilizing reduced tillage approaches offer the greatest potential for the dual purpose of weed management and enhancement of soil quality, as demonstrated by many conventional no-till studies[19,20]. Despite soil quality enhancement, however, grain crop yields are often equivalent or inferior in no-till systems; results from over 80 studies involving barley, corn, soybean, wheat and other grain crops failed to reveal a consistent yield advantage for no-till compared with tilled systems[21]. In semi-arid portions of the North Central region, however, crop performance has been shown to improve by eliminating tillage, due to the proposed more efficient plant water use[22–24]. In comparisons between organic and conventional no-tillage systems, Miller et al.[25] found equal or greater winter wheat yields in an organic system compared to a conventional, no-tillage cropping system in a 4-year study. No-till vegetable systems have also produced mixed results. In a review of no-till vegetable systems by Rogers et al.[9], increased yields over tilled systems were determined in 10 out of 16 comparisons. Despite inconsistent yield advantages, planting small grains and N-fixing cover crops together may be an effective management strategy to simultaneously increase soil C and optimize the soil N cycling processes, thereby reducing leaching loss of N.

While typical methods for terminating cover crops in organic systems can include mowing, roll-chopping, undercutting and roto-tilling[26], the rolling or rolling/crimping system recently has been promoted for optimum termination and mulch layering. Steel rollers with blunt blades welded onto cylindrical drums have been used to terminate cover crops in conservation tillage systems for many years in South America[27], but the roller/crimper designed by The Rodale Institute (Kutztown, Pennsylvania, USA) in 2002 consists of steel blades welded on a large steel cylinder in a chevron pattern to facilitate a crimping motion to more effectively terminate fall-planted cover crops in the following spring[28]. Prior to cover-crop termination, the roller/crimper is filled with water to provide an additional 907 kg to aid in mechanical termination, with the goal of creating a dense cover-crop mulch capable of suppressing weeds and eliminating additional weed control throughout the season. In contrast to mowing, the roller/crimper is a more controlled operation, typically resulting in a more flattened, uniform mulch layer amenable to no-tillage planting equipment. Grain and vegetable seeds or transplants are planted simultaneously or in another pass into the flattened cover crop, using no-till drilling of seeds, high-residue transplanters, or hand-transplanting. The ability to mount the roller/crimper on the front of the tractor so that cover crop termination and no-till seeding of the subsequent crop can occur in a single pass has led to successful production of corn, soybean, tomatoes, pumpkins (*Cucurbita pepo* L.) and strawberries (*Fragaria* × *ananassa*) in Pennsylvania using the Rodale roller/crimper[28].

The objective of the present experiment was to compare: (1) the effects of an organic no-tillage system using a roller/crimper and two cover crop combinations (hairy vetch/rye and winter wheat/Austrian winter pea) with a tilled organic system on corn, soybean and irrigated tomato plant growth, pest (weeds, insects and disease) management and yield; and (2) the economic performance of the organic no-tillage system to the tilled organic

system. This systems research was conducted on a certified organic site at an Iowa State University research farm to demonstrate the feasibility of these techniques to meet certified organic regulations.

Materials and Methods

A site at the Iowa State University Neely-Kinyon Farm in Greenfield, Iowa, was selected for this experiment, where the predominant soil was a moderately well-drained Macksburg silty clay loam (fine, smectitic, mesic Aquic Argiudolls) with a uniform slope of 0–2%. All operations and inputs were in compliance with organic regulations[3], and the Iowa Department of Agriculture and Land Stewardship (Des Moines, Iowa) certified the site as organic. Prior to this experiment, no research on organic no-tillage production had occurred in Iowa. Individual plots measuring 6 × 33.5 m (corn and soybean) or 1 × 1.2 m (tomato) were laid out in a randomized complete block design of three treatments with three replications in three separate areas of the farm in fall 2005 and 2006. The treatments in this systems experiment: (1) tilled, with tillage used before and after commercial crop planting; (2) no-tillage cover crop combination of winter wheat ('Expedition' in 2005 and 'Arapahoe' in 2006, Albert Lea Seed House, Albert Lea, Minnesota, USA) (63 kg ha^{-1}) and Austrian winter pea (*Pisum sativum* L. ssp. *arvense* (L.) Poir.) (21 kg ha^{-1}); and (3) no-tillage cover crop combination of rye (VNS) (72 kg ha^{-1}) and hairy vetch (VNS; Albert Lea Seed House) (36 kg ha^{-1}) were established in each crop section. The no-tillage experiment was established in a new site on the farm each year with an intercrop of organic oats (*Avena sativa* L.) and alfalfa (*Medicago sativa* L.) as the previous crop in the rotation for all fields in both years. Following the experiment each year, fields were left with cover crop and commercial crop residue during the winter, and the typical Neely-Kinyon Farm crop rotation (corn to soybeans; soybeans to oats/alfalfa; tomatoes to corn) was followed the next spring, but this rotation was not part of the experiment described herein. Field operations and data collections were conducted at approximately the same time each year, or as close to the same date as weather permitted.

Field operations

Cover crops were planted with a no-till drill (John Deere, Ankeny, Iowa, USA) in no-tillage plots in fall 2005 (September 12) and 2006 (October 31, due to a wet fall). In spring, one disking operation and one field cultivation were conducted in the tilled treatment plots 3 weeks prior to cover-crop termination in no-tillage plots, with an additional field cultivation the day before planting. The cover crops in no-tillage plots were crushed with a roller/crimper implement (3.2 m wide × 41 cm diameter) mounted on a tractor in late May of both years. All cover crop plots were rolled/crimped in one direction, with no roller overlap between passes. In the smaller tomato plots, the same rolling technique was used, with the roller/crimper centered on plot middles, and the edges of the roller/crimper in plot borders. Cover crops were rolled/crimped when the wheat and rye in the mixture reached anthesis or Zadoks growth stage 60 (visible pollen shedding), following protocols from previous research[27]. Before rolling/crimping, the roller/crimper was filled with water to aid in crushing cover crops. Corn and soybean crops were planted in all plots on the same day as rolling/crimping. Organic soybean seed ('Blue River 3F43' in 2006 and 'BR34A7' in 2007) was planted at 494,210 seeds ha^{-1} in 76-cm rows in organic-tilled treatment plots (John Deere planter, Ankeny, Iowa, USA), following typical planting rates for organic farmers in the area, while soybeans in no-tillage plots were drilled into the crushed cover crop at the same plant population as the tilled treatment in 19-cm rows (John Deere no-till drill, Ankeny, Iowa, USA). The newer organic soybean variety in 2007 contained a similar genetic profile (large-seeded, high-protein and soymilk variety) as the 2006 variety. Corn seed ('BR67M07' in 2006, and the similar 'BR63H07' in 2007) was planted at 79,073 seeds ha^{-1} in 76-cm rows in all plots. No fertilization was applied to corn plots, due to the farmer-expressed need for evaluating no-tillage corn performance using cover crops as the sole nutrient source. Weed management in the organic tilled treatment plots consisted of two rotary hoeings and two row cultivations, per local organic-farming recommendations. No weed management was conducted in no-tillage plots. Corn and soybeans were harvested with a combine (John Deere) equipped with an on-board weighing system in late October 2006 and early November 2007.

Tomato plots were managed following local organic protocols that included hand-transplanting tomato seedlings (30.5 × 61 cm spacing) into each rolled cover crop or tilled treatment plot. Transplants were side-dressed with 2300 kg ha^{-1} of composted swine manure at the time of transplanting, per local farmer practices. Average nutrient content of the compost was 1.9, 2.4 and 3.5 kg t^{-1} N, P and K, respectively, providing an estimated 44 kg N ha^{-1}. Weeds in the tilled plots were hand-hoed every 2 weeks during the growing season. Irrigation was applied through overhead sprinklers, as needed, based on rainfall events. Ripe tomato fruits (≥ 7.6 cm) were hand-harvested from 10 randomly selected plants per plot from August 14 to September 26, 2006 and from August 20 to September 12, 2007. Fruits were counted and immediately weighed for yield estimates.

Data collection

Soybean and corn plant populations were estimated in the month following planting, following protocols in previous organic research[7]. Corn and soybean plant heights were estimated only in the first season by measuring the highest

point of three randomly selected plants per plot to determine whether there was a difference in early plant growth between treatments. Weed populations were estimated in corn and soybean plots in 2007 by counting broadleaf and grass weeds within a 0.84-m^2 quadrat in three randomly selected areas within each plot in June[7]. Sampling for corn borer [*Ostrinia nubilalis* (Hübner)] occurred in late June 2007 (none detected in 2006) by inspecting the whorl of three corn plants (V-6 stage) per plot and recording corn borer larvae presence. At harvest, corn and soybean grain weights were immediately determined, followed by standardization of weights to kg ha^{-1} at 15.5 and 13% moisture, respectively.

Tomato plant height was estimated by measuring the highest point of three randomly selected plants per plot in July and August each year. Weed populations were estimated in the same months each year, with an additional assessment in September 2006. Weed management in organic tilled plots did not occur until after weed populations were counted. In order to determine any differences in reproductive capacity between treatments, early season fruit numbers were determined in July each year and in August 2006 on three plants per plot. Tomato plants were assessed for disease symptoms in July 2006; no disease was detected in 2007. Diseased leaves were collected and plant pathogen diagnosis was confirmed by the Iowa State University Plant Disease Clinic (Ames, Iowa).

Economic analysis

An enterprise budget, which included an estimate of the costs and returns of producing organic corn, soybean and tomato, was developed for this study, following methods of Chase et al.[29]. In economic terms, enterprise budgets help to allocate costs for land, labor and capital to the most appropriate use, as prioritized by the producer. The economic analysis included detailed accounting of fixed and variable costs for inputs (fuel, equipment depreciation, seeds, crop fertility sources and labor), subsequent yields and selling price of organic crops. Machinery costs for field operations were determined by applying standardized cost estimates for cultural practices in each tillage system using Iowa State University surveys[30,31]. Gross revenue was determined by multiplying certified organic prices received for the crop by the average yield obtained in each treatment. Returns to management were calculated by subtracting production costs, including labor and land charges, from gross revenues.

Data analysis

With rainfall differences between years, there was also a significant difference in treatment effects between years (data not shown). Thus, data are presented by each year separately. Individual year crop growth, yield, weed and pest population data were subjected to analysis of variance and mean separation using Fisher's Protected LSD at $P \leqslant 0.05$.

Results and Discussion

Cover crop growth and termination

Germination of the hairy vetch, rye, wheat and winter pea cover crop seed was excellent in both years of the experiment. Thirty days after cover-crop planting in both years, cover was established on 95% of the plot area, with legume plants in each treatment averaging 7.6 cm in height (data not shown). In Spring 2006 and 2007, when cover crops were rolled/crimped prior to planting field crops, two to three rolling/crimping operations were required to completely terminate any erect cover crop plants after each pass, in contrast to the desired 'one-pass' system. Wheat/winter pea mixture plots were rolled/crimped two times while those in the rye/hairy vetch mixture were rolled/crimped three times. Even after the third rolling/crimping, hairy vetch plants continued to grow in approximately 10% of the plot area. With the exception of some of the vetch plants, rolled/crimped cover crops lost vigor and appeared as a dry, killed mulch layer approximately 3 weeks after rolling/crimping.

Crop growth and yield

Corn response. Limited rain in June and July 2006 increased soil moisture competition between cover crops and corn and soybean plants. Rainfall during June 2006 was 8.1 cm below the 30-year average monthly precipitation; July rainfall was 2.8 cm below normal amounts, while 2007 rainfall met the 30-year averages. As a result of low rainfall in 2006, cover crop competition, and potential N immobilization (not directly measured), no-tillage corn plants were smaller and had lower plant stands than tilled plants (Table 1). Corn yield was greatly reduced (by 42% in 2006 and 92% in 2007) in the no-tillage treatments compared to the tilled system. These results contrasted with Pennsylvania organic no-till corn yields, which reached 9598 kg ha^{-1} in a rolled hairy vetch cover crop[32]. Yield reductions in conventional reduced tillage systems have been associated with cooler soils[33,34], insufficient fertility[35], or less effective weed management in some cases[36]. Differences between the more promising yields in other states and the poor corn growth and yield in the organic no-tillage system in Iowa may be correlated with several factors: less severe winter weather in the mid-Atlantic states supporting enhanced hairy vetch survival; later physiological stage of cover crop at rolling/crimping; and sandier soil allowing more consistent crimping of cover crop stems. Associated with higher yields, hairy vetch was terminated in the early-pod stage in Wisconsin[37] compared to a 25% bloom stage in Iowa. By delaying rolling until hairy vetch early-pod stage, cover crop termination would likely improve, since the rye cover crop

Table 1. Corn growth and yield in the organic no-tillage experiment, 2006 and 2007, Greenfield, Iowa.

	2006			2007	
Treatment	**Plant population (plants ha^{-1})**	**Plant height (cm)**	**Yield (kg ha^{-1})**	**Plant population (plants ha^{-1})**	**Yield (kg ha^{-1})**
No cover (tilled)	62,394a[1]	248a	9710a	54,158	7777a
Rye/hairy vetch cover crop (no-till)	59,510ab	213b	5668b	45,302	628b
Wheat/winter pea cover crop (no-till)	51,479b	193c	5567b	49,834	640b
LSD (0.05)	8231	7.11	946	NS	969

[1] Means followed by the same letter down the column for each year are not significantly different at $P \leqslant 0.05$ according to Fisher's protected LSD test. Yield based on 15.5% moisture.

Table 2. Soybean growth and yield in the organic no-tillage experiment, 2006 and 2007, Greenfield, Iowa.

	2006			2007	
Treatment	**Plant population (plants ha^{-1})**	**Plant height (cm)**	**Yield (kg ha^{-1})**	**Plant population (plants ha^{-1})**	**Yield (kg ha^{-1})**
No cover (tilled)	140,850b[1]	104a	2197a	355,787	3170a
Rye/hairy vetch cover crop (no-till)	226,719a	66b	1067b	308,733	2724b
Wheat/winter pea cover crop (no-till)	209,422a	66b	1042b	275,357	2862b
LSD (0.05)	32,539	3.5	301	NS	289

[1] Means followed by the same letter down the column each year are not significantly different at $P \leqslant 0.05$ according to Fisher's protected LSD test. Yield based on 13% moisture.

in the mixture would be past anthesis, which was found to improve the effectiveness of rolling/crimping[38]. The most critical issue with delayed planting, however, would be obtaining adequate grain yields with a shorter-maturity corn variety.

Soybean response. Rotary-hoeing operations appeared to negatively affect soybean plant populations in the tilled treatment in 2006, which had lower plant populations than both no-tillage cover-crop treatments (Table 2), but crop stand differences were not observed in 2007. Similar to corn response, soybean plant height and yields were reduced in the no-tillage treatments. In one of the two years (2007), no-tillage soybeans averaged 2793 kg ha^{-1}, which was similar to the tilled organic soybean yield of 3170 kg ha^{-1}, but statistically lower. Bernstein et al.[37] obtained organic no-tillage soybean yields in Wisconsin similar to our results, with 24% greater yields in tilled over no-tilled fields. Thelen et al.[39], however, obtained 4167 kg ha^{-1} in soybean intercropped with rye in Michigan, suggesting a higher yield potential with this system.

Tomato response. In contrast to no-tillage corn and soybean, the irrigated no-tillage tomato system had similar agronomic responses as the tilled system (Table 3). Plant height and early fruit number varied between sampling periods, but in general, the no-tillage treatments did not decrease plant growth compared to the tilled treatment. Irrigated tomato yields averaged 40 t ha^{-1} in 2006 and 63 t ha^{-1} in 2007, with no statistical differences between treatments. Of the two no-tillage treatments, the hairy vetch/rye cover crop produced numerically higher yields, which were only 2% lower than tilled plots each year. Our results were similar to those of Teasdale and Abdul-Baki[40] and Abdul-Baki et al.[41] who obtained statistically equal yields in tilled and no-tillage tomatoes planted into a hairy vetch mulch. Creamer et al.[42] also demonstrated statistically equal yields between organic tomatoes grown in an undercut cover-crop mixture of hairy vetch, rye, crimson clover and barley and conventionally fertilized tomatoes. In California, organic tomato yields were found to be statistically equal in no-tillage and tilled treatments only when cover crop re-growth did not occur[43]. During periods of low rainfall, Mills et al.[44] reported 29% lower no-till tomato yields compared to those grown with black plastic mulch. Thus, in order to obtain the highest returns with no-tillage vegetable crop systems, adequate irrigation must be provided. While the response to no-tillage conditions has been generally positive with tomato crops, results from reduced-tillage bell pepper (*Capsicum annuum* L.) and zucchini (*Cucurbita pepo* L.) production have ranged from statistically equal[45] to 20–50% reduced no-tillage yields[33,46]. In those cases where yield reductions

Table 3. Tomato plant growth and yield in the organic no-tillage experiment, 2006 and 2007, Greenfield, Iowa.

	2006						2007				
	Plant height (cm)		Fruit (number/plant)				Plant height (cm)		Fruit (number/plant)		
Treatment	27 June	14 August	11 July	14 August	Harvested fruit (number ha^{-1})	Yield ($t\,ha^{-1}$)	24 June	1 August	17 July	Harvested fruit (number ha^{-1})	Yield ($t\,ha^{-1}$)
No cover (tilled)	24a[1]	90a	1.1a	43a	1,230,276	49.7	76b	194	1.8b	1,594,494	64.7
Rye/hairy vetch cover (no-till)	23a	86ab	0.6b	37ab	1,091,541	44.1	89a	189	3.0ab	1,440,928	63.3
Wheat/winter pea cover (no-till)	20b	82b	0.2b	30b	878,655	35.5	90a	183	5.5a	1,351,948	63.1
LSD (0.05)	1.8	6.0	0.5	7.7	NS	NS	7.1	NS	2.6	NS	NS

[1] Means followed by the same letter down the column each year are not significantly different at $P \leqslant 0.05$ according to Fisher's protected LSD test.

Table 4. Soybean and corn pest parameters in the organic no-tillage experiment, 2007, Greenfield, Iowa.

		Weed populations (weed number m^{-2})				
		June 7		June 21		
Crop	Treatment	Broadleaf species	Grass species	Broadleaf species	Grass species	Corn borer evidence (% with feeding damage)
Soybean	No cover (tilled)	2.8b[1]	2.8	0.2b	0.2	–
	Rye/hairy vetch cover crop (no-till)	2.2b	2.8	0.2b	0.1	–
	Wheat/winter pea cover crop (no-till)	6.5a	2.3	7.3a	0.3	–
	LSD (0.05)	2.7	NS	2.2	NS	–
Corn	No cover (tilled)	2.2b	1.3b	1.0b	0.1b	8.3
	Rye/hairy vetch cover crop (no-till)	10.2ab	0.7b	6.8b	0.3b	8.3
	Wheat/winter pea cover crop (no-till)	18.3a	13.3a	22.0a	44a	16.7
	LSD (0.05)	11.3	4.20	7.4	5.4	NS

[1] Means followed by the same letter down the column each year for each crop are not significantly different at $P \leqslant 0.05$ according to Fisher's protected LSD test.

occurred, poor cover crop seed coverage, reduced soil temperatures and N immobilization during cover crop decomposition were reported. In previous research in Iowa, higher soil N was present when cover crops were tilled compared to strip-tilled, leading to recommendations for side-dressing composted manure in organic strip-tilled organic pepper production to improve yields[45]. Success of conservation tillage systems has also been reported to be dependent on minimum cover crop mulch disturbance during seeding or transplanting operations[47].

Weed populations and pest levels

Weed populations were greater overall in corn and soybean no-tillage plots than in tilled plots in 2007 (Table 4). Despite the initial adequate mulch layer provided by both rolled/crimped cover crops, the rye/hairy vetch mulch tended to suppress weeds more than the wheat/winter pea treatment over all comparisons. Throughout the season, the wheat/winter pea mulch layer degraded at a greater rate than the rye/hairy vetch

Table 5. Tomato pest parameters in the organic no-tillage experiment, 2006 and 2007.

Treatment	Weed populations (weed number m^{-2})										Disease (% infected)
	2006						2007				2006
	20 July		14 August		13 September		17 July		13 August		11 July
	Broadleaf species	Grass species	Broadleaf species	Grass species	Broadleaf species	Grass species	Grass species	Broadleaf species	Grass species	Broadleaf species	
No cover (tilled)	16.0b[1]	18.4	0.1	0.9a	0.5	13.1	2.3	74	4.5a	16.0	5.0
Rye/hairy vetch cover (no-till)	1.2a	11.0	0.1	0.9a	0.2	7.2	4.5	29	1.0b	7.3	6.1
Wheat/winter pea cover (no-till)	0.9a	7.9	0.1	18.0b	0.1	8.4	2.8	44	3.3a	11.5	7.4
LSD (0.05)	8.8	NS	NS	14.5	NS	NS	NS	NS	1.3	NS	NS

[1] Means followed by the same letter down the column each year are not significantly different at $P \leq 0.05$ according to Fisher's protected LSD test.

mulch (data not shown), leading to more open sites for weeds. In the tomato plots, weeds in no-tillage plots were lower or statistically equal to tilled plots (Table 5), particularly in the hairy vetch/rye plots, but the potential for increasing the weed seedbank when weeds are not managed below economic threshold levels is a concern in long-term organic no-tillage fields. Greater weed management can be obtained in organic no-tillage systems, provided fields have adequate mulch biomass and complete cover crop termination, as Walters and Young[33] have reported up to 80% control of common annual weeds in winter rye stands. Other research, however, has demonstrated greater weed populations in organic wheat, tomato and bell pepper no-tillage systems, respectively[25,43,46]. In our results, weed populations were not found to interfere with irrigated tomato production as much as in rain-fed no-tillage corn and soybean plots, where weeds and hairy vetch re-growth extensively competed with crop growth.

Pest insect response occurred in corn plots only. Corn borer damage in 2007 ranged from 8% in tilled and no-tillage hairy vetch/rye plots to 17% in the no-tillage wheat/winter pea treatment (Table 4), with no significant difference between treatments. Overall, there was a low rate of *Septoria lycopersici* leaf spot in tomato plots (< 8% in 2006; none detected in 2007), with no statistical differences observed between treatments.

Economic comparisons

Corn production costs and returns. Organic corn production costs differed by the tillage system in both the years of experiment, with similar costs across all systems in hourly labor rate at US\$10.50 h^{-1} (2006) and US\$11.00 h^{-1} (2007); interest, charged on all pre-harvest variable costs, including field operations, seed and labor, at a rate of 7.5% in 2006 and 8% in 2007; and land rent at US\$358 ha^{-1} (2006) and US\$383 ha^{-1} (2007). Machine labor was assessed on the basis of time involved in conducting field operations. Total costs in 2006 ranged from US\$786 ha^{-1} in the tilled system to US\$867 ha^{-1} in the hairy vetch/rye no-tillage system (Table 6). Three cost categories—pre-harvest machinery, seed and harvest machinery—contributed the most to cost variation, with the cover-crop system contributing additional costs for seed and management. In this analysis, pre-harvest machinery costs included fixed and variable costs for field operations prior to harvest, while harvest machinery cost included fixed and variable costs for combining plus handling, hauling and drying. The latter three costs were incurred on a 'per kg of grain' basis so there was a direct relationship between total harvest machinery costs and yield. Total production costs for 2007 segregated in the same fashion as 2006, ranging from US\$762 to US \$877 ha^{-1}, with the same three categories contributing to differences between systems. Selling price for organic corn in 2006 was US\$0.24 kg^{-1} and US\$0.35 kg^{-1} in 2007.

Table 6. Economic analysis of organic corn under tilled and no-tillage production, Greenfield, Iowa, 2006 and 2007 (US$ ha^{-1}).

		2006 no-tillage system			2007 no-tillage system	
Operations/inputs	2006 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop	2007 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop
Pre-harvest machinery	70.30	42.38	42.38	72.15	43.74	43.74
Seed	118.61	270.58	160.89	143.91	295.88	186.19
Fertilizer	0.00	0.00	0.00	0.00	0.00	0.00
Crop insurance, miscellaneous, interest	49.00	55.92	50.43	58.81	66.17	60.32
Harvest machinery	166.85	123.31	122.24	145.00	70.99	71.12
Labor	23.87	16.88	16.88	25.01	17.67	17.67
Land (cash rent equivalent)	358.30	358.30	358.30	383.01	383.01	383.01
Total costs	786.93	867.36	751.13	827.90	877.47	762.05
Yield (kg ha^{-1})	9710	5668	5567	7777	628	640
Gross revenue	2,389.21	1,394.61	1,369.90	2,694.24	217.45	221.80
Return to management	1,602.28	527.25	618.78	1,866.34	(660.02)	(540.25)

Table 7. Economic analysis of organic soybean under tilled and no-tillage production, Greenfield, Iowa, 2006 and 2007 (US$ ha^{-1}).

		2006 no-tillage system			2007 no-tillage system	
Operations/inputs	2006 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop	2007 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop
Pre-harvest machinery	88.34	60.42	60.42	90.69	62.27	62.27
Seed	53.37	205.34	95.65	56.04	208.01	98.32
Fertilizer	0.00	0.00	0.00	0.00	0.00	0.00
Crop insurance, miscellaneous, interest	40.97	46.60	41.12	46.90	52.83	46.97
Harvest machinery	50.16	47.25	47.15	52.34	51.37	51.67
Labor	50.61	17.64	17.64	53.00	18.48	18.48
Land (cash rent equivalent)	358.30	358.30	358.30	383.01	383.01	383.01
Total costs	641.76	735.56	620.28	681.99	775.99	660.74
Yield (kg ha^{-1})	2197	1067	1042	3170	2724	2862
Gross revenue	1,383.79	672.13	656.31	2,059.01	1,769.52	1,859.22
Return to management	742.03	(63.43)	36.03	1,377.02	993.54	1,198.49

Returns to management by tillage system for organic corn crops ranged from US$527 ha^{-1} in the hairy vetch/rye no-tillage system to US$1601 ha^{-1} in the tilled system in 2006. In 2007, when no-tilled corn yields were extremely low, there were substantial losses of –US$660 ha^{-1} and –US$540 ha^{-1} in the hairy vetch/rye and the wheat/winter pea no-tillage systems, respectively. With no-tillage corn yields averaging 58% of those in tilled plots in 2006 and 8% of those in tilled plots in 2007, the economic analysis showed that yields and the resulting gross revenue contributed more to returns per hectare than differences in costs, showing the organic no-tillage corn system as financially unviable for those years.

Soybean production costs and returns. Soybean production costs in 2006 were US$642 ha^{-1} in the tilled system and US$736 ha^{-1} in the hairy vetch/rye no-tillage system (Table 7). Costs in the wheat/winter pea no-tillage system were similar to the tilled system, accruing US$620 ha^{-1}. Soybean production costs varied between systems in the same categories as shown for the corn production system. Total production costs for 2007 ranged from US$682 ha^{-1} in the tilled system to an average of US$718 ha^{-1} in the no-tillage system. Management in the tilled system included both the time involved for the field operations and for 'walking' soybeans (hand-weeding) at 2.5 h ha^{-1}. Hand-weeding was not conducted in the no-tillage treatments, due to a sufficient mulch layer formed by the cover crop after termination. Soybean prices were US$0.63 kg^{-1} in 2006 and US$0.65 kg^{-1} in 2007. Similar to the corn economic analysis, tilled soybeans returned more to management, due to higher yields and higher gross revenues. Tilled soybeans returned US$742 ha^{-1} in 2006 compared to a loss of US$14 ha^{-1} from the no-tillage plots, which averaged 55% lower yields

Table 8. Economic analysis of organic tomatoes under tilled and no-tillage production, Greenfield, Iowa, 2006 and 2007 (US$ ha^{-1}).

		2006 no-tillage system			2007 no-tillage system	
Operations/inputs	2006 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop	2007 tilled system	Hairy vetch/rye cover crop	Wheat/winter pea cover crop
Machinery	25.13	28.19	28.19	25.77	28.47	28.47
Transplants and cover crop seed	1,524.89	1,676.86	1,567.17	1,524.89	1,676.86	1,567.17
Compost	44.85	44.85	44.85	44.85	44.85	44.85
Crop insurance, interest, miscellaneous	857.38	862.10	858.67	955.58	960.62	959.44
Labor (hand-planting/ weeding/harvest)	25,856.81	25,856.81	25,856.81	27,088.09	27,088.09	27,088.09
Land (cash rent equivalent)	358.30	358.30	358.30	383.01	383.01	383.01
Total costs	28,667.36	28,827.12	28,713.99	30,022.19	30,181.90	30,068.55
Yield (t ha^{-1})	49.7	44.1	35.5	64.7	63.3	63.1
Gross revenue	65,696.92	58,288.21	46,920.86	85,536.02	83,752.42	83,531.50
Return to management	37,029.58	29,461.09	18,206.87	55,513.83	53,570.52	53,462.95

than tilled plots. In 2007, when average no-tillage soybean yields were only 12% lower than tilled soybeans, no-till returns to management averaged US$1096 ha^{-1} compared to US$1377 ha^{-1} for tilled soybeans, suggesting that no-tillage soybean production can be competitive in years of adequate rainfall. The economic returns for organic no-till soybeans were similar to those obtained in previous experiments, where higher organic soybean yields concomitantly matched 25% greater economic returns in the tilled system[37].

Tomato production costs and returns. Tomato production costs by tillage system ranged from US$28,667 ha^{-1} in 2006 to US$30,022 ha^{-1} in 2007 in the tilled system, to an average of US$28,771 ha^{-1} in the no-tillage system in 2006 and US$30,125 ha^{-1} in 2007, reflecting few differences in production costs among systems (Table 8). Field operations, except for plot preparations, were based on manual labor, representative of small-scale organic vegetable operations in the area. Compost rates included a unit cost of US$0.02 kg^{-1}, averaging US$45 ha^{-1} across all treatments. Tomato prices were held constant at US$1.30 kg^{-1} for the 2-year period. Because production costs were stable each year among tillage treatments, differences in returns to management primarily resulted from yield differences. As previously indicated, the highest numerical yields were obtained in the tillage treatment in both the years of study, and the additional costs for cover crops and rolling/ crimping lowered no-tillage economic returns.

Conclusions

Economic risks from low no-tillage yields are often weighed against the positive benefits of soil erosion prevention and improvements in soil quality in no-tillage production[48]. Methods to decrease tillage in organic crop production will greatly advance soil conservation on organic farms, but 'green payments' for soil conservation efforts[49] are needed to offset yield and economic losses. While the development of a successful no-tillage system for organic production remains our goal, organic systems that rely on tillage may not necessarily decrease soil quality if additional C sources are routinely added to the soil, as required under certified organic rules. Teasdale et al.[50] reported higher soil combustible C and N after 9 years in an organic system that included cover crops compared with three conventional, no-tillage systems, two of which included cover crops. C budgets developed after 10 years of organic production in Iowa showed that a 4-year organic cropping system (corn–soybean–oats–alfalfa) can potentially sequester as much soil organic C (0.53 Mg C ha^{-1} yr^{-1} in the top 15 cm) as a conventional no-tillage system[51] based on prudent amounts of tillage, coupled with crop rotations, cover crops and compost applications. Additional research in organic no-tillage systems in Iowa will examine soil quality aspects, particularly for organic no-till soybeans, where successful yields consistently have been obtained[52]. The development of cover crop varieties that mature in early spring under Midwest conditions and continued research on improved roller/crimper prototype design to allow complete termination of cover crops in one pass is needed to advance organic reduced- or no-tillage systems[53].

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Progress towards no-till organic weed control in western Canada

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Abstract

Organic farmers in western Canada rely on tillage to control weeds and incorporate crop residues that could plug mechanical weed-control implements. However, tillage significantly increases the risk of soil erosion. For farmers seeking to reduce or eliminate tillage, potential alternatives include mowing or using a roller crimper for terminating green manure crops (cover crops) or using a minimum tillage (min-till) rotary hoe for mechanically controlling weeds. Although many researchers have studied organic crop production in western Canada, few have studied no-till organic production practices. Two studies were recently conducted in Saskatchewan to determine the efficacy of the following alternatives to tillage: mowing and roller crimping for weed control, and min-till rotary hoeing weed control in field pea (*Pisum sativum* L.). The first study compared mowing and roller crimping with tillage when terminating faba bean (*Vicia faba* L.) and field pea green manure crops. Early termination of annual green manure crops with roller crimping or mowing resulted in less weed regrowth compared with tillage. When compared with faba bean, field pea produced greater crop biomass, suppressed weeds better and had less regrowth. Wheat yields following pea were not affected by the method of termination. Thus, this first study indicated that roller crimping and mowing are viable alternatives to tillage to terminate field pea green manure crops. The second study evaluated the tolerance and efficacy of a min-till rotary harrow in no-till field pea production. The min-till rotary hoe was able to operate in no-till cereal residues and multiple passes did not affect the level of residue cover. Field pea exhibited excellent tolerance to the min-till rotary hoe. Good weed control occurred with multiple rotary hoe passes, and pea seed yield was 87% of the yield obtained in the herbicide-treated check. Therefore, this second study demonstrated that min-till rotary hoeing effectively controls many small seeded annual weeds in the presence of crop residue and thus can reduce the need for tillage in organic-cropping systems.

Key words: blade roller, cover crops, knife roller, mechanical weed control, minimum tillage, rotary hoe, organic weed control, roller crimper, zero-tillage

Introduction

No-till farming on the Canadian Prairies can now be considered the 'conventional' farming system since no-till methods are used in more than 60% of the area in some provinces[1]. The area seeded to certified organic crops also increased from 2000 to 2007 and has stabilized at approximately 576,000 ha[2]. Organic crop production relies heavily on tillage for weed control and incorporation of residues from cover or green manure crops. Tillage can result in less crop residue on the soil surface, exposing the soil to wind and water erosion. A long-term crop rotation experiment in Saskatchewan found that surface residue levels were frequently insufficient to protect against erosion and 35–50% of land under organic systems was at high risk for serious erosion[3]. There has been significant research in organic crop production on the Canadian Prairies (reviewed by Knight et al.[4]); however, there has been very little research focusing on no-till organic production. Recently, Vaisman et al.[5] investigated the use of a blade-roller for terminating green manure crops to reduce the amount of tillage associated with this practice. Since there is little published research on western Canadian no-till organic production to review, we recently conducted two studies related to this. Our results are presented in this article.

Green manure crops are grown for the purpose of leaving their nutrient-rich biomass on the land rather than harvesting and removing it. They are essential to organic cropping systems because they provide nutrients to subsequent crops and suppress weeds[6]. However, green manure crops are usually terminated with tillage,

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increasing the risk of soil erosion. A potential solution may be using a roller–crimper to terminate green manure crops. Roller–crimpers have been successfully used to kill fall rye prior to the planting of no-till organic soybean[7]. An objective of the first study was to determine the short- and long-term effects of terminating green manure crops by roller crimping compared with tillage and mowing.

Mechanical weed control can be effective in controlling weeds[8,9]; however, most post-emergence tillage implements do not perform well in the presence of crop residues[10]. If minimum or no-till organic farming is going to be a reality, a mechanical tool that is able to control weeds and operate in the presence of crop residues is required.

The rotary hoe is not a common implement on the Canadian Prairies. It has two sets of spiked wheels with spoon-shaped tips attached to the ends of the tips[10]. and is operated at speeds of 10–20 km h^{-1}; therefore, it can cultivate large parcels of land in a relatively short time frame. A minimum tillage (min-till) rotary hoe can work in the presence of crop residues because extender arms provide greater separation between the front and back wheels, preventing plugging of the implement with straw.

No research has been conducted on the performance of a min-till rotary hoe under no-till conditions on the Canadian Prairies. As part of our second study, we conducted two experiments to evaluate the potential for the min-till rotary hoe as a weed management tool in no-till production of field pea. The first experiment evaluated the following: (1) the ability of a min-till rotary hoe to operate in standing stubble and maintain surface residues, and (2) the tolerance of field pea to rotary hoeing at different crop stages and hoeing intensities. The second experiment determined the timing and number of min-till rotary hoe passes required to optimize weed control and grain yield in field pea.

Materials and Methods

First study: green manure termination experiment

This experiment determined the effect of two no-till methods of green manure termination (mowing and crimping) on faba bean and pea green manures at three different crop stages. The experiment was conducted at the Kernen Research Farm (52°09′N, 106°33′W; elevation 528 m) near Saskatoon, SK and at a commercial organic farm (52°19′N, 106°05′W; elevation 508 m) near Vonda, SK. Both sites are on black chernozemic clay loam soil (USDA classification: clayey, mixed, frigid, typic haplustoll soil). Both sites were seeded on land previously cropped to spring wheat (*Triticum aestivum* L.) that had been under organic production for over 10 years. The experimental design was a three-way factorial randomized complete block design (RCBD), with the factors being crop (field pea and faba bean), termination method (tillage, mowing and crimping) and termination timing (early flower, late flower and early pod fill). Treatments were repeated four times in 4 × 6 m plots. Each site-year of the experiment ran for 2 years, with the green manure treatments applied in year 1 followed by a wheat re-crop in year 2 on all plots. The experiment was initiated at the same two sites in 2008 and 2009, resulting in four site-years.

The forage cultivars 4010 (field pea) and CDC SSNS-1 (faba bean) were used for green manure crops. Pea and faba bean were planted at the recommended rates of 88 seeds m^{-2} for pea and 44 seeds m^{-2} for faba bean. Plots were managed according to certified organic practices. Termination methods included flail mowing (mowing), a single pass with a tandem disk (tillage) and a single pass with a roller–crimper[11].

There were three timings for the termination based on the stage of pea development: early flower (BBCH 61), late flower (BBCH 67) and late pod fill (BBCH 76)[12]. In mid-September, weed regrowth following termination was sampled by harvesting green weed biomass. All treatments were then tilled with a cultivator to kill the remaining weeds and prepare the soil for seeding the following spring. Crop and weed biomass were sampled at each operation from two 0.25 m^2 quadrats per plot; the biomass was separated into crop and weeds and oven dried prior to weighing.

In the year following the green manure treatments, the land on all treatments was cultivated prior to planting spring wheat (cv. CDC Go) at 250 seeds m^{-2}. The wheat was harrowed for weed control at the two-leaf stage. We collected data on wheat biomass at physiological maturity, wheat seed yield and protein content.

Second study: rotary hoe experiments

The rotary hoe study consisted of two experiments. Both experiments were conducted at the Scott Research Farm (52°21′N, 108°51′W; elevation 650 m) near Scott, Saskatchewan on a loam soil (Canadian soil classification: dark brown cherozem; USDA soil classification: typic boroll). The soil contains 31% sand, 42% silt and 27% clay. Soil organic matter content is 4% and the soil pH is 6.0.

Rotary hoe experiment 1

This experiment was conducted in 2004, 2005 and 2006 to investigate the tolerance of field pea to rotary hoeing at various development stages. The experimental design was a split-plot, and the treatment design was factorial with four replicates. Plot size was 3 × 6 m. The treatment of the main plots was the crop development stage of field pea at the time of rotary hoeing: pre-emergence (BBCH 07), ground-crack (GC) (BBCH 09), the three above-ground node stages (BBCH 13/33), the six above-ground node stage (BBCH 16/36) and the nine above-ground node stage (BBCH 19/39). The treatment of the sub-plots was

Table 1. ANOVA for fixed effects of green manure termination study. Saskatoon and Vanscoy, SK, Canada 2007–2010.

Source	df	Emergence	Crop biomass	Weed biomass	Crop regrowth	Weed regrowth	Year 2 wheat yield	Year 2 weed biomass	Year 2 wheat protein
		Plants m^{-2}				kg ha^{-1}			%
Crop (C)	1	0.001	0.021	0.114	0.030	0.484	0.642	0.712	0.087
Termination (T)	1	–	–	–	0.716	0.059	0.059	0.447	0.434
Stage (S)	1	–	0.0002	0.321	0.064	0.068	0.270	0.384	0.101
C×T	1	–	–	–	0.708	0.273	0.034	0.284	0.831
C×S	1	–	0.192	0.315	0.048	0.061	0.527	0.242	0.689
T×S	1	–	–	–	0.772	0.022	0.656	0.339	0.985
C×T×S	1	–	–	–	0.585	0.472	0.876	0.811	0.165

the number of rotary hoe passes (0–6 passes) conducted at each stage.

Field pea (cv. CDC Sonata) was seeded directly into standing spring wheat stubble with a zero-till hoe drill at a rate of 80 viable seeds m^{-2}. The only tillage received by the plots was that of the min-till rotary hoe. All plots were maintained weed-free with two herbicide treatments in the fall prior to the study: ethafluralin and imazethapyr were applied to the soil surface at 1100 and 12.5 g ai ha^{-1}, respectively.

Rotary hoeing was done with a 3 m Yetter min-till rotary hoe (Yetter Manufacturing Inc., Colchester, IL, USA). Hoeing was done at a speed of 12 km h^{-1}. At each crop stage, the passes were done sequentially, with one pass conducted in the direction that the crop rows were seeded and alternating passes performed in the opposite direction.

To assess the effect of rotary hoeing on crop surface residues, digital photos of each treatment (number of passes) were taken when the field pea was hoed at the pre-emergence stage. The images were projected on a computer screen, and a 10×10 grid was then overlaid on the photos. Surface residue cover was calculated as the percentage of grid intersections that lie over crop residue.

Tolerance data included field pea density (plants m^{-2}) measured 3 weeks after treatment and crop yield.

Rotary hoe experiment 2

This experiment evaluated the efficacy of rotary hoeing in field pea. Prior to seeding, wild mustard (*Sinapis arvensis* L.) and green foxtail (*Setaria viridis* L.) were broadcast at a rate of 100 seeds m^{-2} over the entire experimental area. There was a large population of indigenous wild oat (*Avena fatua* L.) in the second year of the study.

A factorial treatment design was employed with single, double and triple passes applied to field pea at the GC, GC followed by the same treatments at the three above-ground node stage (GC-3N), and GC followed by the same treatments applied at the three and five above-ground node stages (GC-3N-5N). The GC, 3-node and 5-node stages correspond to BBCH growth stages 09, 13/33 and 15/35, respectively. An untreated check and herbicide treatment were also included. The herbicide treatment consisted of imazamox applied at 20 g ai ha^{-1} with a registered adjuvant at the three above-ground node stage of field pea. Experimental design was RCBD with four replicates. The plot size was 3×6 m.

Using a zero-till hoe drill, the field pea (cv. Sonata) was cross-seeded into standing cereal stubble at a rate of 100 viable seeds m^{-2}. Since the plots were cross-seeded, the rotary hoe treatments were applied perpendicular to the field pea rows.

The following data were collected: field pea density measured 3 weeks after the final hoeing treatments, weed density and biomass (fresh weight) by species at crop maturity, and crop yield.

In the analyses, year and year-by-treatment interactions were considered a random effect, and data were combined over years if there was no significant year-by-treatment interaction. For experiment 2 data are presented by year because the dominant weed species varied between years.

Results and Discussion

First study: green manure termination experiment

Averaged over all termination timings, pea had a threefold greater biomass than faba bean (Table 1, Figure 1A). The lower biomass in faba bean may be partially because the recommended target plant population of faba bean is one-half that of pea (44 versus 88 plants m^{-2}). Faba bean has a large seed; therefore, its target plant population is low to keep the seeding rate low and affordable. The faba bean cultivar CDC SSNS-1 was chosen for its small seed size[13]; however, even though the faba bean target population was lower, the weight per area seeding rate was similar to pea since the seed weight of faba bean was approximately double that of pea (287 versus 133 mg $seed^{-1}$).

As the green manure stage of termination was delayed, both green manure crops accumulated more biomass

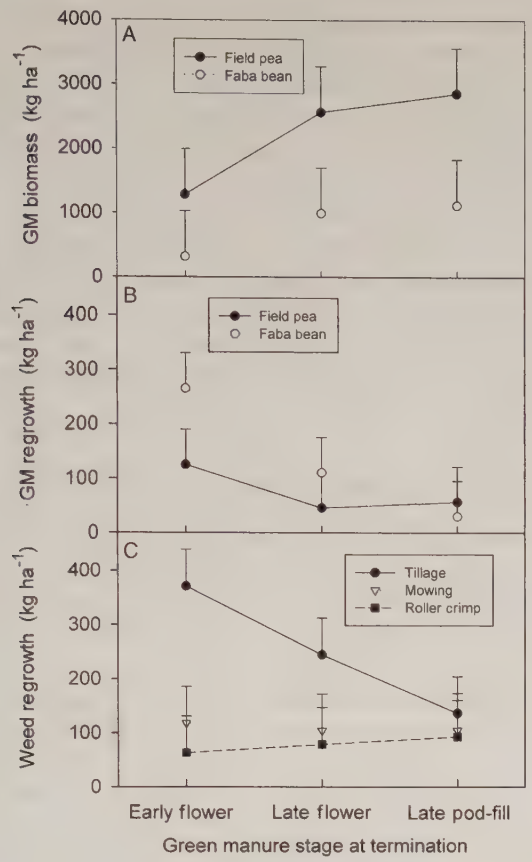

Figure 1. Effect of green manure stage at termination on: (A) green manure crop biomass, (B) green manure crop regrowth and (C) weed regrowth, as affected by termination method. Average of four site-years. Bars indicate standard error.

(Fig. 1A). The accumulation from early flower to late flower was greater than that from late flower to late pod.

Faba bean tended to have higher though not statistically significant weed biomass than field pea ($P=0.11$; Table 1). However, at three of the four site-years, the difference in weed biomass between faba bean and field pea was highly significant, while one site-year did not have a significant difference (data not shown). The lower faba bean biomass accumulation reflects its lower competitiveness, which allows for greater weed regrowth. We also observed that faba bean had a much sparser canopy with more erect plants than field pea, which also may allow for greater weed growth. The field pea variety 4010 has been observed to be very competitive with weeds[14].

The effect of crop regrowth following termination depended on the interaction of crop and timing (Table 1 and Fig. 1B). There was little regrowth in pea regardless of the crop stage at termination. At the early flowering stage faba bean had greater regrowth than pea (Fig. 1B). At later stages, there were no differences between the regrowth of faba bean and pea. There was no difference in crop regrowth between termination methods (Table 1 and Fig. 1A) because tillage does not kill all plants. Because there was no effect of termination method on crop

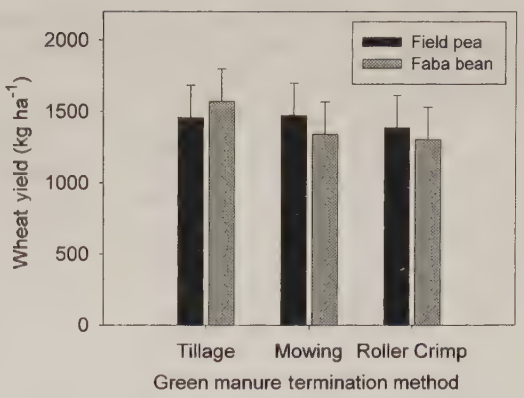

Figure 2. Effect of green manure crop and termination method on the following year's wheat yield. Average of four site-years.

regrowth, we concluded that roller crimping and mowing are effective termination methods for faba bean and field pea green manure crops. Roller crimping had to be conducted during flowering in order to effectively terminate fall rye (*Secale cereale* L.)[6]; therefore, the timing for effective roller crimping is crop dependent. Pea may be well suited for use as an annual green manure terminated with a roller crimper since there was little regrowth regardless of termination method or crop stage.

Weed growth following termination was greatest when tillage was conducted at the early flowering stage (Table 1 and Fig. 1C). With later terminations, there were no differences in weed growth among termination methods. There was a significant crop by stage interaction (Table 1); however, inspection of the results indicated no meaningful effect (data not shown).

Faba bean appears to be an inferior choice for a green manure crop compared with field pea. It had lower crop biomass and allowed greater weed biomass production. The total weed and crop biomass production were similar for both crops; however, with peas most of the biomass was crop. It is possible that the low biomass yields of the faba bean were due to pest problems. In two of the site-years, blister beetles (*Lytta nuttalli*) were a problem; they partially defoliated the faba beans and appeared to reduce biomass accumulation. However, the sites without blister beetles still had reduced yields compared with peas.

Overall, the type and timing of green manure crop termination had little effect on the following year's wheat crop. Wheat yield was affected by the interaction between termination method and the previous crop (Table 1 and Fig. 2). When pea was the previous green manure crop, the termination method had no effect on wheat yield. Terminating the faba bean by tillage resulted in higher wheat yields compared with mowing or roller crimping. Vaisman et al.[5] found that in two of three site-years, replacing tillage with roller crimping resulted in a linear reduction of wheat yields as tillage operations were eliminated. The yield reduction was found to be associated with reduced nitrogen mineralization in the roller–crimper treatments. In contrast to Vaisman et al.[5], we did

Table 2. ANOVA and effect of min-till rotary hoe passes on percent surface crop residue, field pea density and field pea seed yield. Scott, SK, Canada 2004–2006.

	Surface residue	Field pea density	Field pea yield
	----------Means----------		
Number of passes	(%)	No. per m^2	$kg\,ha^{-1}$
0	64	56	2445
1	61	61	2436
2	58	56	2443
3	61	55	2318
4	56	52	2293
5	59	53	2256
6	55	53	2286
$LSD_{0.05}$	12	4	116
Source	----------*P* value----------		
Crop stage (CS)	NA[1]	0.22	0.66
No. of passes (NP)	0.76	<0.01	<0.01
CS × NP		0.17	0.52
Polynomial contrasts (for passes)			
Linear	–	<0.01	<0.01
Quadratic	–	0.65	0.49
Cubic	–	0.01	0.32

[1] Not applicable—surface residue data only collected at one crop stage (Pre-).

not attempt to eliminate tillage from the cropping system; rather, we eliminated tillage associated with terminating the green manure crop.

There was a trend towards greater protein concentration in wheat following pea than following faba bean (Table 1). Timing of green manure termination also had an effect on the protein concentration of wheat the following year, with the earliest timing resulting in the highest wheat protein concentration (data not shown).

Second study: rotary hoe experiment 1

The number of rotary hoe passes did not have a significant effect on the level of surface residue ($P=0.763$) (Table 2). In all years, surface residue was maintained at greater than the 30–50% ground cover that is required to prevent wind or water erosion[15].

We evaluated crop tolerance by assessing the hoeing effect on field pea density. Crop stage had no effect on plant density; however, the number of passes had a significant linear effect on plant density ($y=-1.0357x+58.25$; $r^2=0.55$) (Table 2). A single pass resulted in slightly higher crop density than the untreated control, and plants declined by about one plant for every pass conducted after that (Table 2). Plant density never dropped below 50 plants m^{-2}, the point at which lower densities tend to result in reduced grain yields[16]. The differences in plant mortality were not likely biologically significant; field pea was able to tolerate up to six passes of a min-till rotary hoe at all crop stages evaluated.

Crop stage at rotary hoeing had no effect on field pea yield, and there was no crop stage by number of passes interaction on yield (Table 2). As crop yield indicates the crop's ability to recover from rotary hoeing; crop recovery was similar at all crop stages. Increasing the number of passes resulted in a linear decline in crop yield, independent of crop stage (Table 2). Based on a linear regression model ($y=-35.2x+2459.4$; $r^2=0.83$), each pass reduced field pea yield by 35 $kg\,ha^{-1}$. Overall, compared with the untreated check, pea yield declined by about 7% with six passes; therefore, the impact of hoeing on crop yield under weed-free conditions was negligible.

Second study: rotary hoe experiment 2

The number of rotary hoe passes had no effect on field pea density at any crop stage in either year, showing that field pea tolerated rotary hoeing in weedy conditions, irrespective of crop stage and the number of passes (Table 3).

Weed density was higher in 2007 than in 2008, with respective mean densities of 176 and 82 plants m^{-2} (data not shown). In 2007, the predominant weed species were wild mustard and green foxtail, with respective densities of 101 and 30 plants m^{-2}. Indigenous populations of common lambsquarters (*Chenopodium album* L.) and wild buckwheat (*Polygonum convolvulus* L.) were also present. The same species were present in 2008; however, wild mustard densities were very low, with a mean density of 6 plants m^{-2}. Green foxtail and wild oat densities were 39 and 23 plants m^{-2}, respectively, which was approximately 40 and 28% of the total weed density. Green foxtail densities were not high enough to cause significant yield loss in field pea; therefore, wild oat was the predominant weed leading to crop interference in 2008.

Both crop stage and the number of rotary hoe passes had an effect on weed density in 2007, but neither had an effect in 2008 (Table 3). This indicates that the large-seeded wild oat may be more tolerant of rotary hoeing than small-seeded weeds. In 2007, rotary hoeing reduced weed density by about 20% for each successive stage that it was conducted (Table 3). Lowest weed densities were achieved with a double pass, but no significant reductions occurred with a triple pass.

Crop stage and number of passes had a significant effect on weed biomass in 2007. Although the *P*-values for stage and passes were not significant for 2008, means separation detected significant differences (Table 3). The lowest weed biomass was obtained by conducting a double or triple pass at all three growth stages (GC-3N-5N) in 2007. Conducting rotary hoeing at all three growth stages resulted in a 75% reduction in weed biomass compared with the untreated check. The herbicide treatment reduced weed biomass by 93% compared with the untreated control in 2007 (Table 3).

Table 3. Means and ANOVA for min-till rotary hoe efficacy study in field pea. Scott, SK, Canada 2007–2008.

	Field pea density				Total weed density				Weed biomass				Field pea yield			
	2007		2008		2007		2008		2007		2008		2007		2008	
	Means															
	No. per m^2								$g\,m^{-2}$				$kg\,ha^{-1}$			
Stage[1]																
GC	78	ns	77	ns	144	a	65	ns	198	a	716	a	2127	b	4268	ns
GC-3N	78	ns	70	ns	119	b	65	ns	230	a	564	ab	2564	a	4296	ns
GC-3N-5N	82	ns	74	ns	96	c	64	ns	112	b	499	b	2645	a	4191	ns
Passes																
RH single	66	ns	71	ns	143	b	61	bc	250	b	734	ab	2132	c	3938	c
RH double	77	ns	78	ns	108	c	64	b	141	c	525	b	2600	b	4414	b
RH triple	79	ns	71	ns	108	c	67	b	149	c	518	b	2604	b	4402	b
Untreated (UT)	74	ns	81	ns	179	a	101	a	455	a	826	a	1176	d	3884	c
Herbicide (H)	107	ns	83	ns	88	d	60	bc	33	d	238	c	3367	a	5079	a
	P values															
Source																
Stage (S)	0.81		0.5		0.03		0.91		0.01		0.11		<0.01		0.75	
Passes (P)	0.73		0.39		0.06		0.87		0.01		0.07		<0.01		<0.01	
S×P	0.99		0.74		0.55		0.54		0.27		0.47		0.17		0.71	
Contrasts																
UT versus RH	0.17		0.26		0.07		0.1		<0.01		0.39		<0.01		0.04	
H versus RH	0.01		0.18		0.23		0.21		<0.01		<0.01		<0.01		<0.01	
UT versus H	<0.01		0.87		0.04		0.03		<0.01		<0.01		<0.01		<0.01	
Pass linear	0.83		0.23		0.99		0.87		0.8		0.94		0.97		0.93	
Pass quadratic	0.45		0.49		0.02		0.54		<0.01		0.02		<0.01		<0.01	

[1] GC (ground-crack), 3N (3-node) and 5N (5-node) correspond to BBCH stages 09, 13/33 and 15/35, respectively.
Means followed by different letters are significantly different at $P<0.05$.

In 2008, the GC-3N-5N stage had lower weed biomass than the GC stage but was not significantly different than the GC-3N stage (Table 3). Both the double and triple passes had similar biomass, which was significantly lower than the GC stage and the untreated check. On average, the best rotary hoe treatments and the herbicide treatments resulted in a 40 and 71% reduction in weed biomass compared with the untreated control in 2008 (Table 3).

The greater reduction in weed biomass from rotary hoeing in 2007 is likely due to the weed species present. In 2007, small-seeded broadleaf and grassy weeds were dominant, and in 2008 wild oat was more prevalent. This indicates that rotary hoeing is more effective on small-seeded, shallow-rooted weed species than on large-seeded, well-anchored weed species. This observation is consistent with results from studies evaluating the efficacy of pre- and post-emergence harrowing in grain crops[1,4,8,9].

Crop stage and the number of passes had a significant effect on grain yield in 2007, while the number of passes had a significant effect in 2008 (Table 3). In 2007, rotary hoeing at the GC stage resulted in 80% higher yields than those obtained in the untreated check. Subsequent rotary hoeing at the 3-node stage improved yields by 20% compared with the GC stage, while additional hoeing at the 5-node stage did not improve yields compared with hoeing at the GC-3N stage. In 2007, a single pass improved yields by 81% compared with the untreated check, and a double pass further improved yield by 22%. A triple pass, however, was not significantly higher yielding than the double pass. Herbicide application resulted in a 2.9-fold increase in grain yield over the untreated check, whereas the highest yielding rotary hoe treatments resulted in a 2.2-fold increase over the untreated check. Min-till rotary hoeing resulted in as much as 89% of the grain-yield attained by herbicide application.

In 2008, rotary hoeing at the GC stage resulted in 10% higher yields than in the untreated check, with no improvement by rotary hoeing at subsequent growth stages. A single pass did not increase grain yield compared with the untreated check, but a double pass resulted in 14% higher yields. Conducting more than a double pass at the GC stage did not improve grain yield. Herbicides improved grain yield by 31% compared with the untreated check. In 2007 a double pass at the GC stage resulted in 87% of the grain yield attained by herbicide application, which was similar to the results attained with the best rotary-hoeing treatment that year.

Field pea yields were more than 50% higher in 2008 than in 2007 (Table 3). Growing conditions were more conducive to pea production in 2008 due to higher precipitation, particularly in the month of July. In addition,

mean daily air temperatures were above average in July 2007, and field pea can be sensitive to high temperatures during the flowering period. The yield responses from weed control were much lower in 2008 under the more favorable environmental conditions for field pea production.

Conclusions

Terminating a field pea green manure crop with a roller crimper is a viable option for reducing tillage in organic crop production. Wheat following the roller crimper treatment had seed yields that did not differ from plots that were terminated with mowing or tillage. Plots terminated by tillage actually had greater regrowth of weeds following crop termination compared with mowing or roller crimping. As crimping has much lower energy requirements compared with mowing it is preferable. Furthermore, with crimping the crop residue remains attached to the ground, potentially reducing erosion. Field pea was a superior annual green manure crop than faba bean, with field pea having greater biomass accumulation, greater weed competition, reduced regrowth following termination, and lower seed costs.

The min-till rotary hoe provides partial annual weed control in organic no-till cropping systems. It worked well in the presence of standing cereal-crop residues and was able to maintain residues on the soil surface even after multiple passes. Field peas exhibited good tolerance to multiple passes at numerous growth stages. The min-till rotary hoe was particularly effective at controlling small-seeded weeds in field pea, where it achieved 87% of the yield achieved with herbicide application. The min-till rotary hoe will not likely effectively control perennial weeds, which are a major challenge to no-till organic production.

The roller–crimper and min-till rotary hoe exhibited potential to reduce tillage in organic-cropping systems; however, further research and innovation are required for no-till organic agriculture to become a reality in western Canada.

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Impact of reduced tillage on soil organic carbon and nutrient budgets under organic farming

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Abstract

No-tillage (NT) and reduced tillage (RT) systems are well-known management tools for reducing soil erosion and improving soil fertility. NT and RT may improve the environmental and economic performance of organic farming, but they are still not common practice among organic farmers. This paper presents the effects of tillage [RT versus conventional tillage (CT)], fertilization (slurry versus manure compost) and biodynamic preparations (with versus without) on soil fertility indicators such as soil organic carbon (C_{org}), microbial biomass and microbial activity, soil nutrients and nutrient budgets in an organic farming system during the first six-year crop rotation period of a long-term experiment on a clayey soil in a temperate climate. RT caused stratification of soil organic carbon (C_{org}), microbial properties and soil nutrients in the soil profile. Under RT, C_{org} in the 0–10 cm soil layer increased from 2.19 to 2.61% (w/w) from 2002 to 2008, whereas it remained constant under CT. In both tillage treatments, C_{org} remained constant in the 10–20 cm soil depth. Microbial biomass C increased by 37% under RT in the 0–10 cm soil depth and microbial activity [dehydrogenase activity (DHA)] was enhanced by 57%. Soil microbial biomass C and DHA in the 10–20 cm soil depth were also higher under RT (+10 and +17%, respectively). Soluble soil P and K were 72 and 40%, respectively, higher in 0–10 cm soil depth under RT when compared with CT. Fertilization showed no effects on the measured soil properties. Biodynamic preparations increased solely the C_{mic}-to-N_{mic} (soil microbial biomass C to soil microbial biomass N) ratio by 7% in the 0–10 cm soil depth. Nutrient budgets for P were balanced in all treatments, but N and K exports were higher under RT compared to CT. We conclude that RT is a suitable method for increasing indicators of soil fertility in organic farming systems. The combined effects of RT and an organic farming system with a diverse, ley-based crop rotation and organic fertilization merit further promotion and it may be considered for supporting actions by the agricultural policy schemes.

Key words: conservation tillage, soil fertility, organic fertilization, biodynamic preparations, nutrient budget, soluble soil nutrients

Introduction

Soil erosion and other forms of soil degradation are major problems facing agriculture today. Soils are not renewable over a human timescale. Most arable soils are prone to degradation, mainly caused by soil mismanagement. The degradation processes are more dependent on 'how' rather than on 'what' crops are grown[1], highlighting the importance of sustainable soil and crop management.

No-tillage (NT) and reduced tillage (RT) systems are well-known management tools for preventing soil erosion and conserving soil fertility[2]. A positive effect on soil organic carbon (C_{org}) contents in the superficial soil layer has frequently been reported[2–7], whereas the effects on C_{org} in the whole profile are still a matter of controversy[8]. NT and RT cause a stratification of C_{org} and microbial properties in the soil profile[3,6,9,10]. The intensity of tillage operations in RT and the amount and management of above-ground crop residues affect the degree of stratification. Total N, organic N, mineralizable N, P and K usually follow the same pattern with a concentration in the surface layer and no change or decrease below[10].

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Organic farming practices are reported to have a positive impact on air, soil, ground and surface water and biodiversity[11]. Multiple cropping systems, crop rotation, cover crops, organic fertilizers and minimum tillage can add organic matter to the soil and increase its capacity to circulate nutrients, air and water[11]. Crop production in organic farming relies and depends on nutrient transformation processes in the soil[12]. Soil quality is thus an important factor in organic farming and C_{org} is a lynchpin in this system. C_{org} in the topsoil is driven by interacting influences of climate, topography, soil type and aspects of crop management such as fertilization, tillage and crop rotation[10]. Conversion of natural land to crop production and tillage generally leads to a loss of C_{org}[13].

C_{org} was reported to remain constant in an organic farming system including ley-based crop rotations and application of organic fertilizers, while it decreased under conventional farming with mineral fertilization[12]. Munro et al.[14] found organically managed topsoils to contain a higher percentage of organic matter, total N and available P when compared with their conventionally managed counterparts at 14 paired sites in England. Drinkwater et al.[15] argue that the higher quality of added organic matter in organic farming leads to an accumulation of C_{org}. Microbial communities are key regulators of soil organic matter dynamics and nutrient availability[16]. Soil microbial biomass and activity, both indicators of biological soil fertility, are enhanced by organic farming[12,16]. To ensure both short-term productivity and long-term sustainability, achieving a balance between inputs and outputs of nutrients is critical, especially as the use of imported materials to build soil fertility is restricted under organic farming[17]. Suitable crop rotations containing legumes produce surpluses in the N budgets of organic farms. P and K budgets show both surpluses and deficits, depending on the farm type and the import of nutrients[17,18].

The International Federation of Organic Agriculture Movements[19] recommends that organic farmers 'take measures to prevent erosion, compaction, salinisation and other forms of soil degradation'. Loss of topsoil should be minimized 'through minimal tillage, contour ploughing, crop selection, maintenance of soil plant cover and other management practices that conserve soil'.

Although conservation tillage (NT and RT) may improve the environmental and economic performance of organic farming, it is still not very common among organic farmers[10]. There are major concerns about the adoption of conservation tillage. Increased weed pressure under conservation tillage as a result of mechanical weed control techniques not adapted to high levels of crop residues on the surface would appear to be the main problem. Topsoil compaction, especially during the first years of transition and with limited availability of N mainly at the beginning of the growing season, also impedes conversion to conservation tillage. Well-drained clays, stable loams and calcareous soils combined with moderate precipitation are favorable conditions for conservation tillage under organic farming conditions. Suitable crop rotations with a high weed-suppressing capacity include a ley phase, cover crops and intercropping[10].

The incorporation of the ley is a critical point under RT[10,20]. Only a few experiments have investigated RT under organic farming conditions. Severe weed competition[20–22] and technical difficulties while incorporating grass–clover sods[20] led to the conclusion that an occasional use of the moldboard plough is inevitable to overcome weed pressure under RT in organic farming[23]. Schulz et al.[24] consistently found similar yields in CT and RT, when at least shallow turning of the soil was carried out. The stratification of C_{org}, soil nutrients and microbial properties with RT in organic or conventional farming systems all developed in a similar way. Under organic farming, RT changed the allocation of C_{org} within the topsoil but did not enhance C_{org} over the whole investigated soil profile[24]. Emmerling[25] reported an increase in C_{org} in the 0–25 cm soil depth where C_{org} was enhanced in the upper layer (0–15 cm) and decreased in the layer below (15–25 cm). Microbial biomass and microbial activity in these soils were stratified under RT; there was an overall increase in microbial properties but the content of plant-available P in the investigated soil layer did not change[25].

Conservation tillage (NT and RT) in organic farming has not yet been successfully adapted and further research into the adaptation of conservation tillage to different soils and climatic conditions, the development of suitable crop rotations and management practices to promote weed control and new strategies to remove and incorporate leys in a conservation tillage system are required[10]. The influence of different fertilization strategies in organic farming systems with and without livestock on N-mineralization and thus on reduced N supply under conservation tillage is not yet clearly understood.

In the present experiment the implementation of RT in an organic farming system with livestock was studied. Two fertilization strategies, the effects of biodynamic preparations and their interactions with soil tillage were investigated. Results of the conversion period from CT to RT showed an increase in C_{org}, microbial biomass and microbial activity in the superficial soil layer over the first 3 years. In the first experimental period, average yields of cereals and sunflowers under RT were 93% of those obtained under CT[26]. After conversion, yields of fodder crops such as grass–clover and silage maize were 29% higher under RT, despite a considerably higher weed infestation of silage maize under RT[27], directing the focus on soil fertility. This paper presents the effects of tillage, organic fertilization strategies and biodynamic preparations on soil fertility indicators such as C_{org}, microbial biomass, microbial activity, soil nutrients and nutrient budgets after the first 6-year crop rotation period of a long-term experiment on a clayey soil in a temperate climate.

Table 1. Dates of soil tillage in the different tillage systems.

System	Crop	Tillage	Date
Conventional	Winter wheat	Plough	October 11, 2002
		Rototiller	October 30, 2002
	Intercrop—Oat–clover	Rototiller	August 19, 2003
	Sunflower	Plough	February 26, 2004
		Rototiller	April 22, 2004
	Spelt	Plough	November 8, 2004
		Rototiller	November 16, 2004
	Grass–clover	Rototiller	August 13, 2005
	Silage maize	Plough	February 25, 2008
		Rototiller	May 9, 2008
Reduced	Winter wheat	Rototiller	October 30, 2002
		Chisel	August 6, 2003
	Intercrop—oat clover	Rototiller	August 19, 2003
	Sunflower	Rototiller	April 22, 2004
	Spelt	Rototiller	November 16, 2004
	Grass–clover	Rototiller	August 13, 2005
	Catch crop—winter pea	Stubble cleaner	September 14, 2007
		Chisel	September 15, 2007
		Rototiller	October 11, 2007
	Silage maize	Stubble cleaner	May 9, 2008
		Rototiller	May 9, 2008

Table 2. Organic matter (OM) input (manure, slurry and green manure) in the first crop rotation period (2003–2008) (t OM ha^{-1}).

				Wheat 2003	Sunflower 2004	Spelt 2005	Grass–clover 2006	Grass–clover 2007	Silage maize 2008	Total	Average yearly input
Treatment											
I	Con	MC	P−	2.82	1.08	2.15	2.36	1.30	0.76	10.47	1.75
II	Con	MC	P+	2.68	1.25	2.05	2.30	1.26	0.76	10.31	1.72
III	Con	Slu	P−	2.07	0.72	0.94	2.31	1.39	0.21	7.63	1.27
IV	Con	Slu	P+	2.07	0.72	0.94	2.19	1.38	0.26	7.55	1.26
V	Red	MC	P−	2.82	1.08	2.43	2.33	1.30	2.49	12.45	2.07
VI	Red	MC	P+	2.68	1.25	2.33	2.28	1.26	2.49	12.29	2.05
VII	Red	Slu	P−	2.07	0.72	1.22	2.38	1.39	1.94	9.71	1.62
VIII	Red	Slu	P+	2.07	0.72	1.22	2.25	1.38	1.98	9.62	1.60

Silage maize 2008, RT including pea green manure; OM, organic matter.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.

Material and Methods

Field experiment

In autumn 2002, a field experiment was conducted at Frick, Switzerland (47°30′N, 8°01′E) involving factors such as tillage, fertilization and biodynamic preparations. A detailed description of the experiment is given by Berner et al.[26].

CT uses a moldboard plough operating at 15 cm depth. A chisel plough (15 cm) was used in the RT system and grass–clover in the RT system was superficially incorporated with a stubble cleaner running at 5 cm depth. Seedbed preparation was performed by a rotary harrow in both tillage systems (Table 1).

Inputs of organic matter (Table 2) were higher in the manure compost than in the slurry system due to the use of straw for animal bedding. The experimental farm where the experiment is performed operates at a stocking density of 1.8 livestock units (LU) ha^{-1} consisting mainly of cattle. The farm has 19 ha of grassland and pastures and 13 ha of arable land. Mainly fodder crops are grown and additional fodder for swine breeding is purchased. Fertilization was planned at a stocking density of 1.4 LU ha^{-1}. Differences in fertilization levels of N, P and K were due to different proportions of excreted elements in solid and liquid organic manure types in the stable system and to N losses during manure storage. We aimed at achieving identical fertilization levels for P and thus accepted differences for N and K. Consequently, plots with slurry fertilization received N, P and K at levels of 1.13, 1.41 and 1.17 LU ha^{-1}, respectively. Fertilization with the manure compost treatment was

Table 3. *F*-values and significance levels of the mixed-model with repeated measures in 2002, 2005 and 2008 for pH_{H_2O} and soil organic carbon (C_{org}).

	pH_{H_2O}		C_{org}	
	0–10 cm	**10–20 cm**	**0–10 cm**	**10–20 cm**
Tillage	19.94*	0.69	84.01**	5.35
Fertilization*Preparations	1.61	0.89	1.77	0.7
Tillage*Fertilization*Preparations	1.18	0.58	0.52	1.76
Year	32.54***	17.53**	37.91***	4.67(*)
Year*Tillage	8.33*	0.22	22.82**	0.47
Year*Fertilization*Preparations	2.13(*)	0.36	1.04	0.24
Year*Tillage*Fertilization*Preparations	2.35(*)	1.85	2.24(*)	2.21(*)

(*)$P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

carried out at levels corresponding to 1.18, 1.53 and 1.09 LU ha^{-1} for N, P and K, respectively (see Table 7 for average yearly inputs).

The biodynamic preparations (P) consisted of the following: P 500, cow-manure fermented in a cow horn; P 501, silica stored in a cow horn. These were applied at rates of 250 and 4 g ha^{-1}, respectively and sprayed three times per season on the relevant plots. Composting additives in the biodynamic treatment were yarrow flowers (P 502, *Achillea millefolium* L.), camomile flowers (P 503, *Matricaria recutita*, L.), stinging nettle (P 504, *Urtica dioica*, L.), oak bark (P 505, *Quercus robur*, L.), dandelion flowers (P 506, *Taraxacum officinale*, Wiggers) and valerian flowers (P 507, *Valeriana officinalis*, L.); these were added at the start of manure composting or slurry storage[28,29]. In total, 10 g preparations were added to about 2 t of composted raw material and 10 g preparations were also added to the slurry volume of 20 m^3 with the biodynamic preparations.

The three factors—tillage, fertilization and preparations—were fully factorized. This resulted in eight treatments, each replicated four times. The 32 plots were arranged in a strip-plot design. The plot size was 12 m × 12 m, allowing the use of regular-sized farming equipment. Soil samples were taken and yields were measured in an inner 8 m × 8 m parcel.

Site conditions

The soil type at the experimental site was a Stagnic Eutric Cambisol with 45% clay content [coefficient of variance (cv) 15%] and a pH_{H_2O} of 7.1 (cv 4%). It was enriched in ammonia acetate-EDTA extractable P and K due to extensive application of manure from livestock (swine) in pre-study conventional management.

Before the experiment started, the field was under conventional management and had been managed organically for 7 years in accordance with the European Union Regulation (EEC) No. 834/2007. The ploughing depth was 22 cm under conventional farming and 15 cm under organic farming prior to the start of the experiment. C_{org} in the ploughed soil depth was therefore distributed relatively homogeneously.

The mean annual precipitation at the site was 1000 mm. In rainy periods the soil can be waterlogged for some days. The mean annual temperature was 8.9°C.

Crops

A ley-based rotation was established from 2003 to 2008 (Table 1). Cereal and sunflower grains, cereal straw, the oat–clover intercrop, grass–clover and silage maize were removed from the field. In the RT system only a winter pea catch crop was established before silage maize and incorporated in spring.

Cereal yields were 11% lower under RT compared to CT, whereas sunflower yields were increased by 5% under RT[26]. Yields of grass–clover and silage maize were enhanced by 26 and 34%, respectively in RT plots[27].

Soil sampling

Soil samples were taken at the beginning of the experiment on October 1, 2002 (after harvest of silage maize), on March 15, 2005 (standing crop: spelt) and on September 25, 2008 (after harvest of silage maize) in all 32 experimental plots. Twelve individual cores (diameter 3 cm) per field plot were separated into 0–10 cm and 10–20 cm soil depth layers and thereafter bulked to one composite sample per plot and layer. Soils were then sieved through a 5-mm mesh and kept at 3°C until they were analyzed.

Chemical soil analysis

Measurement of pH and C_{org}. The pH of dried samples (60°C, 24 h) was measured in a soil suspension with deionized water (1:10, w/v). C_{org} was measured after wet oxidation of 1 g of dry soil in 20 ml concentrated H_2SO_4 and 25 ml 2 M $K_2Cr_2O_7$ in accordance with Swiss standard protocols[30].

Measurement of soil nutrient contents. Soluble nutrients P and K were extracted with CO_2-saturated water (P_{CO_2}, K_{CO_2}) according to Swiss standard protocols[30].

The plant-available exchangeable fraction of P ($P_{Aac-EDTA}$) was extracted with ammonium acetate-EDTA. Phosphate in the extract was measured after complex formation with added ammonium molybdate in a spectrophotometer at 750 nm. Available K in the ammonium acetate-EDTA extract ($K_{Aac-EDTA}$) was measured by atom absorption spectrometry at 766.5 nm[30].

Soil microbial analyses

All soil microbial analyses were carried out on moist soil samples adjusted to a water content corresponding to 40–50% of maximum water retention capacity.

Chloroform fumigation extraction (CFE). Soil microbial biomass C (C_{mic}) and N (N_{mic}) were estimated by CFE in accordance with Vance et al.[31]. CFE was done in triplicate on 20 g (dry matter) subsamples that were extracted with 80 ml of a 0.5 M K_2SO_4 solution. Total organic C (TOC) in soil extracts was determined by infrared spectrometry after combustion at 850°C (DIMA-TOC 100, Dimatec, 45276 Essen, Germany). Total N was subsequently measured in the same sample by chemoluminescence (TNb, Dimatec, 45276 Essen, Germany). Soil microbial biomass was then calculated according to the formula: $C_{mic} = EC/k_{EC}$, where EC = (TOC in fumigated samples − TOC in control samples) and $k_{EC} = 0.45$[32]. $N_{mic} = EN/k_{EN}$, where EN = (total N extracted from fumigated samples − total N extracted from control samples) and $k_{EN} = 0.54$[33].

Soil DHA. DHA was measured according to Tabatabai[34] in 5 g of soil samples incubated at 30°C for 24 h in the presence of an alternative electron acceptor [triphenyltetrazolium chloride (TTC)]. The red-colored product [triphenylformazan (TPF)] was extracted with acetone and measured in a spectrophotometer at 546 nm.

Nutrient balances

Nutrient balances for N, P and K were calculated on a field basis. Wheat grains and straw, oat–clover intercrop, sunflower seeds, spelt grains and straw, grass–clover, winter pea and silage maize samples were analyzed for nutrient concentrations. Nitrogen was determined after Kjeldahl digestion. For measuring P and K, samples were incinerated at 600°C and the ash extracted with concentrated hydrochloric acid. N and P concentrations were determined photometrically and K via atom absorption spectrometry. Nutrients (N, P and K) in slurry and manure compost were extracted with hydrochloric acid after the samples had been incinerated at 600°C and were analyzed as specified above. Biological N-fixation by legumes, atmospheric deposition, leaching and gaseous emissions of nutrients were not considered in the balances. The winter pea catch crop contained 62 kg N ha^{-1} and was exclusively incorporated into the soil of the RT system. Although it was assumed that the whole quantity of catch crop N was not fixed biologically, it was included in the nitrogen budget.

Statistics

The statistical model used involved tillage as the main factor in the strip-plot design and Fertilization*Preparations as a combined factor. Soil microbial properties and nutrient contents were calculated with a general linear model to test for significance using SPSS 15.0 software (SPSS Inc., Chicago, Illinois, USA, 2006). Linear contrasts were then calculated for fertilization and preparations using SAS 9.1 software (SAS Institute Inc., Cary, North Carolina, USA, 2002–2003). A mixed model in SAS was used to perform a time line analysis for pH and C_{org} with the fixed factors Tillage, Fertilization*Preparations and Year (Year as a repeated measure). The Block was used as a random factor. In the result tables, first the means of the eight basic treatments were presented. Second the relative differences between the factors tillage, fertilization and preparation were shown. Third, the significant differences between the three factors and respective interactions were depicted. The levels of probability $P < 0.05$, $P < 0.01$ and $P < 0.001$ were declared significantly different.

Results and Discussion

After the first 6-year crop rotation period of the present experiment, statistical analysis revealed no effects of fertilization and only slight effects of preparations on the investigated properties while the response to tillage was strong, especially in the 0–10 cm soil depth layer. A distinct stratification of C_{org}, microbial biomass C and N, microbial activity, plant-available P and K was found under RT, while they were distributed relatively homogeneously throughout 0–20 cm under CT.

pH and C_{org}

A mixed model analysis of variance (ANOVA) with repeated measures in 2002, 2005 and 2008 was used to identify significant changes of pH and C_{org} over the first crop rotation period. The factors Year in both soil layers and Tillage in the 0–10 cm soil layer showed significant effects. There was no effect of the combined factor Fertilizer*Preparations. The interaction Year*Tillage significantly affected pH and C_{org} in the 0–10 cm soil layer (Table 3).

Soil pH deceased significantly from 2002 to 2005 under both tillage treatments and in both soil depths. When compared with the initial values of 2002, pH values in 2008 were significantly lower only under RT (Table 4, Fig. 1). The decrease of pH was highest under RT in 0–10 cm (-0.17, $P < 0.01$).

According to Rasmussen[5], soil acidity under RT increases in the long run by 0.2–0.3 units in topsoil, which may be due to an accumulation of organic acids in the superficial layer[35]. These findings are in agreement with the results of the present experiment. On the other hand, CT may prevent ions from leaching by turning the soil and thus retard acidification of the topsoil[36]. Seasonal differences

Table 4. Means for pH and soil organic carbon (C_{org}) in 2002, 2005 and 2008 in soil depth layers 0–10 cm and 10–20 cm. Results of the mixed model *t*-test for Year* Tillage, indicating significant differences of the means of each treatment in 2005 and 2008 compared with the corresponding means in 2002.

				pH_{H_2O} 2002		pH_{H_2O} 2005		pH_{H_2O} 2008		C_{org} 2002 (%)		C_{org} 2005 (%)		C_{org} 2008 (%)	
				0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Treatment															
I	Con	MC	P−	7.59	7.59	7.37	7.41	7.52	7.48	2.08	2.06	2.25	2.24	2.19	2.16
II	Con	MC	P+	7.59	7.55	7.40	7.40	7.52	7.48	2.19	2.07	2.22	2.21	2.27	2.16
III	Con	Slu	P−	7.70	7.65	7.48	7.51	7.63	7.60	2.09	2.02	2.18	2.10	2.11	2.09
IV	Con	Slu	P+	7.61	7.60	7.45	7.42	7.56	7.52	2.09	2.05	2.20	2.22	2.07	2.13
V	Red	MC	P−	7.64	7.58	7.31	7.34	7.44	7.51	2.24	2.23	2.50	2.31	2.69	2.28
VI	Red	MC	P+	7.53	7.54	7.31	7.38	7.35	7.43	2.23	2.15	2.55	2.28	2.60	2.18
VII	Red	Slu	P−	7.66	7.63	7.41	7.43	7.41	7.48	2.12	2.12	2.41	2.33	2.64	2.13
VIII	Red	Slu	P+	7.51	7.59	7.37	7.41	7.44	7.47	2.16	2.15	2.39	2.22	2.51	2.11
Mean				7.60	7.59	7.39	7.41	7.48	7.50	2.15	2.11	2.34	2.24	2.39	2.15
ANOVA Year* Tillage															
Conventional				–	–	***	***	(*)	n.s.	–	–	*	(*)	n.s.	n.s.
Reduced				–	–	***	**	**	*	–	–	***	(*)	***	n.s.

Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
(*) $P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significantly different.

causing the lower levels measured in spring 2005 cannot be excluded.

Under RT C_{org} in the 0–10 cm soil layer in 2008 was 19% higher ($P < 0.001$) than the initial values in 2002. This represents an increase from 2.19% C_{org} to 2.61% C_{org} within 6 years. C_{org} remained constant under CT (Fig. 1). No significant differences were found in the 10–20 cm soil layer and there were no effects of fertilization or preparations.

C_{org} is considered an important indicator of soil fertility. The increase in C_{org} in our experiment in the 0–10 cm soil layer under RT measured in 2005[26] continued between 2005 and 2008. In a meta-study, Ogle et al.[37] found C_{org} increased by 16% in 0–30 cm depth after 20 years of NT in a temperate wet climate. Alvarez[4] found no differences in C_{org} accumulation between NT and RT. In this meta-study, the amount of C_{org} integrated over 30 cm soil depth under NT and RT was 14% higher than under CT, if only long-term experiments were taken into account. The increase in C_{org} took place only in the 0–15 cm soil layer, and no differences were reported below 15 cm, which corresponds to our findings. Our results are in line with those of Pekrun and Claupein[2], Rasmussen[5], Kladivko[6] and Koch and Stockfisch[7]. Under organic farming conditions, Emmerling[25] reported a relative increase in C_{org} of 7–10% in the surface layer after 10 years of RT, with no differences below the tilled layer. Other studies found an increase in C_{org} in the superficial layer but a decrease in the untilled soil layers below[3,39,40]. Insufficient plant material left on the field may be a reason for the failure of RT to enhance C_{org}. By contrast, input of organic matter via crop rotation and organic fertilizers in the present experiment were high compared to other RT trials (Table 2). This seems to be important, as Baker et al.[8] argue that C_{org} gains in most cases are based only on near-surface samples (0–30 cm). Changes in C_{org} disappear when deeper sampling (below 30 cm) is included. Under organic farming conditions, Schulz et al.[24] found no increase in C_{org} after 12 years of RT but C_{org} was altered by inducing a ley phase into the crop rotation and with amendment of manure. Many authors[2,41,42] argue that periodical use of moldboard ploughing may be inevitable in organic farming to control weed problems. However, high losses of C_{org} have been reported after single-moldboard ploughing in an RT system, proportional to the previous gain under NT or RT in some studies[7,43,44]. In other studies, no changes could be observed in C_{org} after ploughing of NT soils[45–47]. If periodical intervention is only cultivating or ripping and not ploughing, then most of the previously gained C_{org} could be prevented from mineralization[43]. Organic fertilizers, especially manure, enhance more stable fractions of C_{org}[48,49] and thus C_{org} accumulated under RT in stocked organic farming systems may be more resistant to decomposition after moldboard ploughing than in stockless systems. Peigné et al.[10] think that the combined effect of organic farming and RT could also improve the soil organic matter content and consequently soil nutrient reserves in

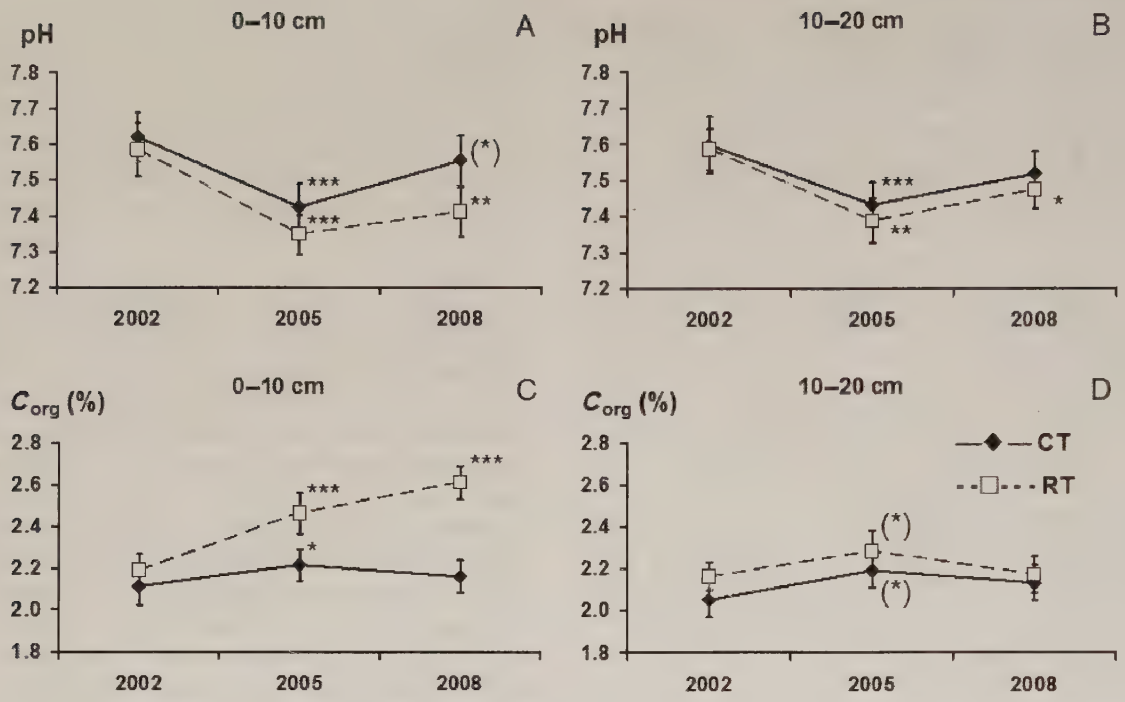

Figure 1. Means and standard error of the mean of pH_{H_2O} and soil organic carbon (C_{org}) in 0–10 cm and 10–20 cm soil depth for RT and CT in the years 2002, 2005 and 2008. A, B: pH. C, D: soil organic carbon [C_{org} (%)]. Results of the mixed model *t*-test for the factor Year*Tillage, stars indicate significant differences of the means of each treatment in 2005 and 2008 compared with the corresponding mean in 2002. (*) $P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

stockless organic systems and call for further research on this issue.

Soil microbial biomass and activity

Soil microbial biomass (C_{mic}, N_{mic}) and microbial activity (DHA) were highly stratified under RT, whereas they were relatively homogeneously distributed throughout the profile under CT. Soil microbial biomass was greater under RT in the 0–10 cm soil layer, C_{mic} being 37% ($P < 0.01$) and N_{mic} 35% ($P < 0.05$) greater than under CT (Table 5). Under RT, C_{mic} was also greater by 10% ($P < 0.05$) than under CT in the 10–20 cm soil layer, whereas N_{mic} showed no significant difference between the two tillage treatments.

Despite 8% higher average values in the 10–20 cm layer, tillage effects on the C_{mic}-to-N_{mic} ratio were not significant. However, a 7% greater C_{mic}-to-N_{mic} ratio ($P < 0.05$) was found with the use of biodynamic preparations.

The C_{mic}-to-C_{org} ratio, which is considered to be an indicator of biological soil fertility[38,50], was 14% greater ($P < 0.05$) under RT than under CT in the 0–10 cm soil layer. Microbial activity (DHA) was greater by 57% ($P < 0.05$) under RT compared to CT in the 0–10 cm soil depth. In the 10–20 cm layer, DHA was greater under RT by 17% as compared to CT ($P < 0.05$).

Microbial biomass and activity are considered to be early indicators of changes in soil properties induced by tillage regimes[9]. A strong differentiation of the microbial biomass between tilled and untilled layers under RT was found in the present experiment; this corresponds with the results obtained by other authors[9,25,51,52]. While we also found greater microbial biomass C in the 10–20 cm soil layer, others reported no difference[9] in ATP contents[36] or less microbial biomass[25,38] in the untilled layer. Microbial biomass is strongly affected by freshly added organic matter[52]. Friedel et al.[36] accordingly found a high dependence of microbial biomass distribution in the soil on the amount of fresh, decomposable organic matter in a tillage experiment. A clear stratification of the microbial biomass depending on the amount of plant residues in different intense silage maize rotation was found by Franzluebbers and Brock[53]. The high input of organic matter in the Frick trial (Table 2) combined with the reduction of tillage may be the reason for the high levels of microbial biomass C and N, even in the untilled 10–20 cm soil layer. The application of manure in the present experiment—in contrast to the stockless experiment described by Emmerling[25], which was also conducted under organic farming conditions with a ley-based crop rotation—may have been a crucial factor in the dynamics of the microbial populations. Heinze et al.[54] found enhanced microbial biomass as a result of application of manure.

Diversified crop rotations, reduction of tillage and adoption of organic farming are reported to result in a more fungal-dominated microbial community[16]. A higher C_{mic}-to-N_{mic} ratio in the undisturbed 10–20 cm soil depth layer under RT in our experiment supports these findings as it indicates a higher proportion of fungi and older cells in

Table 5. Means of soil microbial biomass C_{mic} and N_{mic}, C_{mic}-to-N_{mic} ratio, C_{mic}-to-C_{org} (%) and DHA in the soil depth layers 0–10 cm and 10–20 cm in 2008, ANOVA for the main effects Tillage and Fertilization*Preparations, linear contrasts for fertilization and preparations.

				C_{mic} (mg C_{mic} kg^{-1})		N_{mic} (mg N_{mic} kg^{-1})		C_{mic}-to-N_{mic} ratio		C_{mic}-to-C_{org} (%)		DHA (µg TPF $g^{-1}d^{-1}$)	
				0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Treatment													
I	Con	MC	P−	891	830	132	126	6.82	6.61	3.79	3.92	395	350
II	Con	MC	P+	782	806	113	125	7.03	6.44	3.45	3.80	331	346
III	Con	Slu	P−	773	774	118	123	6.60	6.31	3.72	3.75	323	337
IV	Con	Slu	P+	758	784	108	122	7.12	6.50	3.71	3.72	304	320
V	Red	MC	P−	1090	881	161	129	6.80	6.86	4.11	3.90	532	384
VI	Red	MC	P+	1038	841	146	123	7.27	6.90	4.03	3.93	459	361
VII	Red	Slu	P−	1023	876	152	128	6.75	6.88	3.93	4.17	499	404
VIII	Red	Slu	P+	1046	878	153	127	6.94	6.98	4.23	4.21	489	380
Mean				925	834	135	125	6.92	6.68	3.87	3.92	417	360
Factor													
Tillage													
Reduced (%) (100% = conventional)				137	110	135	101	102	108	114	107	157	117
Fertilization													
Manure compost (%) (100% = slurry)				101	101	101	101	101	99	97	98	101	97
Preparations													
With (%) (100% = without)				98	99	94	98	107	102	100	99	94	98
ANOVA					#								
Tillage				**	*	*	n.s.	n.s.	(*)	*	(*)	*	*
Preparations				n.s.	n.s.	(*)	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.

C_{mic}, soil microbial carbon; N_{mic}, soil microbial nitrogen; C_{org}, soil organic carbon; DHA, dehydrogenase activity; TPF, triphenylformazan.
Con, conventional tillage; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
No statistically significant differences with factor fertilization and no significant interactions between the factors; # ANOVA for C_{mic} in 10–20 cm depth was calculated with C_{mic}^2-values.
(*) $P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significantly different.

Table 6. Means of nutrient contents in the soil depth layers 0–10 cm and 10–20 cm in 2008, ANOVA for the main factors tillage and Fertilization*Preparations, linear contrasts for fertilization and preparations.

				P_{CO_2} (mg kg^{-1})		$P_{Aac-EDTA}$ (mg kg^{-1})		K_{CO_2} (mg kg^{-1})		$K_{Aac-EDTA}$ (mg kg^{-1})	
				0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Treatment											
I	Con	MC	P−	1.93	1.32	112	110	33.6	27.7	479	448
II	Con	MC	P+	1.80	1.14	102	98	31.1	24.3	457	447
III	Con	Slu	P−	1.95	1.20	111	105	30.8	27.4	433	419
IV	Con	Slu	P+	1.62	1.53	106	122	31.7	27.4	447	439
V	Red	MC	P−	3.60	1.46	145	114	44.6	24.4	564	429
VI	Red	MC	P+	3.04	1.26	139	110	43.3	25.5	550	436
VII	Red	Slu	P−	2.81	1.26	132	103	39.9	24.8	546	420
VIII	Red	Slu	P+	3.09	1.56	131	119	50.9	26.5	575	422
Mean				2.48	1.34	122	110	38.2	26.0	506	433
Factor											
Tillage											
Reduced (%) (100% = conventional)				172	107	127	103	140	95	123	97
Fertilization											
Manure Compost (%) (100% = slurry)				109	93	104	96	100	96	102	104
Preparations											
With (%) (100% = without)				93	105	95	104	105	99	100	102
ANOVA											
Tillage				*	n.s.	*	n.s.	(*)	n.s.	*	n.s.
Fertilizer*Preparations				n.s.	n.s.	n.s.	n.s.	(*)	n.s.	n.s.	n.s.

P_{CO_2}, CO_2-extractable phosphorus; K_{CO_2}, CO_2-extractable potassium.
$P_{Aac-EDTA}$, ammonium acetate-extractable phosphorus; $K_{Aac-EDTA}$, ammonium acetate-extractable potassium.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
No statistically significant differences with factors fertilizer and preparations.
(*) $P<0.1$; *$P<0.05$; **$P<0.01$; ***$P<0.001$; n.s., not significantly different.

the total microbial biomass, whereas younger cells and a bacteria-dominated microflora would be reflected in a decrease in the C_{mic}-to-N_{mic} ratio[55]. Guggenberger et al.[56] and Emmerling[25] found an increase in fungi in the upper soil layer under NT and RT. This, however, was not indicated by changes in the C_{mic}-to-N_{mic} ratio in 0–10 cm soil depth in our experiment. The regular use of the roto tiller may have prevented the development of fungal biomass in the tilled layer in our experiment. Additionally, in the experiment described by Emmerling[25], the green fallow and cereal straw were mulched and remained on the field, leaving high amounts of lignin and cellulose as a favorable substrate for the fungal population.

The C_{mic}-to-N_{mic} ratio increased in the present experiment with the use of biodynamic preparations in 0–10 cm. In contrast, Fließbach et al.[12] found a lower C_{mic}-to-N_{mic} ratio for a treatment with compost and biodynamic preparations compared to a manured conventional system. However, they were unable to say whether this effect was caused by composting or by the biodynamic preparations. Minor effects of biodynamic preparations on soil biology properties were found by Carpenter-Boggs et al.[29], when compared with compost without preparations.

The C_{mic}-to-C_{org} ratio in 0–10 cm under RT was 14% greater than that under CT. This difference was already apparent after 3 years of our trial[26] and became smaller than the differentiation by C_{org}. This confirmed the results obtained by Stockfisch et al.[38], who consider the C_{mic}-to-C_{org} ratio to be an early indicator of an enhancement of C_{org}. Angers et al.[40] found a C_{mic}-to-C_{org} ratio three times greater under RT compared to CT in 0–16 cm after 11 years of silage maize rotation and low input of organic matter. An increase in the C_{mic}-to-C_{org} ratio of 16% in the superficial layer was also reported by Emmerling[25].

We measured significantly greater microbial activity (DHA) under RT in both soil layers. Emmerling[25] found soil respiration and alkaline phosphomonoesterase significantly higher in 0–15 cm under RT but no difference in the soil layer below. Similar results were obtained by von Lützow et al.[52] and Kandeler et al.[9]. Von Lützow et al.[52] reported higher microbial biomass and activity in clay soils because the conditions for micro-organisms were more stable, although C_{org} was less accessible to the microbial community.

Phosphorus and potassium

As with C_{org}, microbial biomass and microbial activity, a clear stratification, especially of soluble P_{CO_2} and K_{CO_2}, was found after 6 years under RT. P_{CO_2} in the 0–10 cm soil layer in 2008 was greater by 72% ($P<0.05$) in RT than in CT plots, while the exchangeable $P_{Aac-EDTA}$ was only greater by 27% ($P<0.05$) (Table 6). K_{CO_2} was greater by 40% ($P<0.1$) in RT than in CT in the 0–10 cm layer in 2008

Table 7. Nutrient budgets on a field basis for nitrogen (N), phosphorus (P) and potassium (K) for the first crop rotation period (2003–2008).

				N (kg ha^{-1} yr^{-1}) #			P (kg ha^{-1} yr^{-1})			K (kg ha^{-1} yr^{-1})		
				Input	Yield	Surplus	Input	Yield	Surplus	Input	Yield	Surplus
Treatment												
I	Con	MC	P−	109	113	−4	29	23	7	153	101	52
II	Con	MC	P+	105	122	−17	30	23	7	150	103	48
III	Con	Slu	P−	109	135	−25	24	27	−3	164	125	39
IV	Con	Slu	P+	107	131	24	24	25	−1	164	116	48
V	Red	MC	P−	112	158	−47	30	27	3	159	139	19
VI	Red	MC	P+	108	157	−50	30	26	3	156	138	18
VII	Red	Slu	P−	114	161	−47	25	28	−3	172	140	32
VIII	Red	Slu	P+	111	154	−43	25	27	−2	171	142	29
Mean				109	141	−32	27	26	1	161	126	36

Values presented are annual means. # Biological nitrogen fixation not considered.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.

and $K_{Aac-EDTA}$ was greater by +23% ($P<0.05$). There were no significant tillage effects in the 10–20 cm soil layer and no effects of fertilization or preparations in both layers.

The small differences between the nutrient budgets for P and K in CT and RT cannot be the reason for the high differences in nutrient contents between the two tillage systems. The surplus of K was even greater under CT (Table 7). Yields of forage crops (grass–clover and silage maize) were greater under RT; larger quantities of crop residues and root biomass were also left on the field. Rasmussen[5] reported a significant increase in plant-available P in 0–5 cm soil depth under RT in various studies, while available P in 10–20 cm remained stable or even decreased. A stratification of plant-available P similar to C_{org} was also found by Emmerling[57], whereas the total amount of plant-available P remained constant in 0–25 cm depth. Vu et al.[58] found a concentration of plant-available P in 0–10 cm under NT. A high accumulation of C_{org} was closely related to organic P dynamics, as organic P accumulates only when C availability is high[59]. Plant-available K in the top layer was greater under RT, whereas there were no differences between RT and ploughed soil in 10–20 cm[5].

Nutrient budgets

To ensure both short-term productivity and long-term sustainability, achieving a balance between inputs and outputs of nutrients within the farm system is crucial[17]. As nitrogen fixation by legumes was not considered in our calculation, nitrogen budgets were clearly negative for all treatments. The deficit was −17 kg N ha^{-1} yr^{-1} in the mean of the CT compared to −47 kg N ha^{-1} yr^{-1} in the mean of the RT. P input and removal were balanced, while there was a surplus of K in all treatments over the first crop rotation period (Table 7). K surplus in the conventional treatment (46 kg K ha^{-1} yr^{-1}) was twice that in the reduced treatment (24 kg K ha^{-1} yr^{-1}). Removal of N and K under RT was higher, mainly due to the higher yields of grass–clover and silage maize[27].

If biological N-fixation was considered, N-surpluses of up to 60 kg N ha^{-1} yr^{-1}[18] could be estimated for organic farms in the UK. In a survey considering 88 European organically managed farms, Watson et al.[17] found an average N surplus of 82 kg ha^{-1} yr^{-1} for dairy farms.

Stockless organic farms show P-deficits, while farms with livestock can compensate by importing P in additional feed and bedding material[17,18]. Negative balances of P for organic dairy farms in Norway were reported by Steinshamn et al.[60]. P deficits were also reported by Emmerling[57] in a stockless trial with RT under organic farming conditions.

K budgets calculated for organic crop rotations show both surpluses and deficits[17]. Rotations with large return of manure had K surpluses or balanced K budgets, which is also the case in the present experiment.

To summarize, our results are in agreement with current data in the literature whereby stratification of C_{org}, microbial biomass, microbial activity and soil nutrients were often observed after the adoption of RT. In the 10–20 cm soil layer, we found no differences in C_{org} and soil nutrients between the two tillage systems. Interestingly, soil microbial biomass C and microbial activity (DHA) were also higher in the untilled layer of RT. We found no similar results in the literature and assume that comparatively high inputs of organic material via crop rotation and manure were important factors in the present experiment. The goal of our current research is to target the role of soil types, and of clay minerals in particular, and especially the hydraulic dynamics and aeration of tillage systems. The results presented here reflect the situation after 6 years of RT under organic farming conditions. In their review, Kay and VandenBygaart[3] found results of changes in C_{org} obtained by different investigators to be most consistent when measurements were made more than 15 years after

initiating the tillage trial. Further development of soil fertility indicators need to be assessed, also with respect to carbon sequestration in an organic farming system with diversified ley-based crop rotation and organic fertilization, as carbon sequestration of RT systems is still a matter of controversy[8]. Further research on the combined effects of organic farming and RT on this issue is necessary.

Conclusions

After the first 6-year crop rotation period, only tillage resulted in significant responses in soil fertility indicators. Hardly any effects of the fertilization treatments and the use of biodynamic preparations were observed. We found a strong stratification of C_{org}, microbial biomass, microbial activity (DHA) and soluble soil nutrients such as P and K in the RT tillage system. Enhancement of these properties in the superficial soil layer under RT, accompanied by 11% higher yields, led to the conclusion that RT is a suitable method for increasing soil fertility in organic farming systems. In conclusion, our RT system has demonstrated its capacity to provide a balanced performance with respect to several ecological services of agro-ecosystems, such as primary production, maintenance of soil fertility and natural resources, and nutrient supply[61]. It has to be pointed out that these results were obtained on a clayey soil and similar studies are needed under different pedo-climatic conditions. Moreover, because RT organic farming systems protect soil and improve nutrient use efficiency, they may be considered for agricultural policy support actions.

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Conservation agriculture in Laos: Diffusion and determinants for adoption of direct seeding mulch-based cropping systems in smallholder agriculture

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Abstract

Over the past half-century, major efforts have been made worldwide to develop sustainable alternatives to agricultural tillage. In line with these efforts, two main research development initiatives have supported the experimentation and dissemination of conservation agriculture (CA) in Laos. Here we present the results of a 4-year monitoring and evaluation study conducted in 21 villages targeted for dissemination. In a context of rapid transition to intensive commercial agriculture in Laos, CA has become an important constituent of agricultural landscapes. However, there are significant variations in adoption rates across the study region. Statistical and qualitative evidence suggests that experimentation and adoption are not contingent upon farm-level variables such as capital, labor, age and education. While access to land helps shape local decision-making, the land tenure threshold under which farmers are not willing to experiment with alternative cropping systems is relatively low and highly variable in both space and time. Rather, experience and awareness of land degradation, production costs, social cohesion and leadership appear to be key factors in explaining most variations in local adoption rates. These results indicate that the practice of CA is not necessarily incompatible with smallholder farming. However, while complex crop associations and rotations are necessary for integrated weed control and reduced chemical use, their diffusion would require a broader transformation of the agricultural industry and the current market demand.

Key words: smallholders, agricultural innovation, conservation agriculture, direct seeding mulch-based cropping systems, adoption, South-East Asia

Introduction

Since the 1930s and the so-called Dust Bowl phenomenon in the American Great Plains, there has been increasing concern regarding the long-term ecological and economic impacts of tillage systems. In response to these concerns, a variety of alternatives have been developed worldwide. Practices such as direct seeding emerged in the 1970s among soybean and wheat farmers confronted with severe soil erosion in southern Brazil[1]. Since then the French Agricultural Research Centre for International Development (CIRAD) has been searching for improvements to these practices in collaboration with local farmer organizations, extension agencies and the private sector. Direct seeding mulch-based cropping (DMC) systems were developed based on three principles: no tillage, permanent plant cover, and adapted crop associations and rotations[2,3]. Further efforts were made to adapt these systems to contrasted eco-regions and smallholder farming conditions and to develop more efficient DMC systems that are less dependent on herbicides such as glyphosate[4–8]. DMC systems are now gathered under the

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broad concept of conservation agriculture (CA) and are promoted by major international organizations including the Food and Agriculture Organization (FAO) of the United Nations[9] and Centres of the Consultative Group on International Agricultural Research (CGIAR).

According to global assessments, some 106 million hectares of agricultural land are cultivated using CA or (at least) no-till systems[10,11]. However, important questions have been raised concerning the potential and actual extent of CA in contexts of resource-poor smallholder agriculture[1,12–14]. Factors such as limited access to land, weak land tenure arrangements, limited technical knowledge, limited support from extension agencies, poor access to inputs and markets, and smallholders' need for immediate returns to investment are considered as key constraints preventing the adoption of CA. As argued by Giller et al.[14] (p. 21), while the practice may be a valuable option for medium- or large-scale mechanized farms, it is simply 'inappropriate for the vast majority of resource-constrained smallholder farmers and farming systems'. This paper contributes to the debate by looking at the dissemination and adoption of CA in Laos, a country where small-scale farming is the norm for a majority of the population. It does so through a 4-year agro-economic monitoring of 2160 smallholder farmers and a coupled, statistical and qualitative approach to farm-level determinants for adoption of CA. The paper examines a range of local socio-economic and environmental situations (four districts and 21 villages) and provides empirical evidence for the dynamics of CA adoption in a region that is poorly covered by similar research.

Materials and Methods

Study area

Sayaboury province is characterized by a long border with Thailand and relatively productive soils compared to the rest of the country. The province has long been at the forefront of rural development in Laos and was an important cotton production region from the 1960s to the late 1980s[15]. Since then rapid agricultural expansion and intensification have been underway driven by the growing demand for raw materials from the Thai food-processing and animal feed industries. In the four southern districts of the province, the amount of rainfed cultivated land increased by an average of 53% between 2004 and 2008—going from 1.5 to 2.6 ha per household in Boten district, 2.6 to 3.9 ha in Kenthao, 2.8 to 3.0 ha in Paklay and 0.8 to 1.4 ha in Thongmixay[16].

With the increase in commercial crops such as maize, rice-bean, sesame and peanut, traditional shifting cultivation and crop rotations have been widely replaced by intensive monocropping systems based on mechanical tillage[17,18]. Under these systems, crop residues are generally burned during the dry season and/or directly buried with a mouldboard plough. A commercial hybrid maize variety from Thailand (CP888) is then hand-seeded at the beginning of the rainy season (April–May). In many instances, agricultural intensification has had negative ecological impacts, including increased soil erosion, gradual soil exhaustion and silting up of lowland paddy areas[19]. As monocropping systems have begun to show some limitations in terms of weed control, herbicides are now widely used for land preparation and post-emergence application[20]. Weed control is achieved by a pre-sowing application of glyphosate or Gramoxone; atrazine is also widely used to control broadleaf weeds during the early stages of maize development. Tillage, purchase of hybrid maize seeds and increasingly frequent recourse to herbicides have also resulted in a rapid increase in production costs.

Since the early 2000s, CA has been promoted in Sayaboury as a possible means of achieving the agrarian transition while limiting the negative impacts of land-use intensification. No-till agriculture associated with cover crops, crop rotations or residue conservation have indeed been shown to have positive impacts on soil erosion[21,22], as well as on the maintenance and/or renewal of the soil physical, biological and chemical properties[23,24] and the soil moisture[25]. In a context of small-scale farming where tillage accounts for a significant share of production costs, CA can also be considered as a way to limit farm expenditure. It may also enable diversification of the local economy (e.g., through cover crops and their possible integration in livestock farming systems), hence decreasing the vulnerability of farmers to variations in market prices.

In the light of these potential benefits, a National Agro-Ecology Programme (PRONAE) was established in 2001 to test DMC systems in four villages in southern Sayaboury province. Four years later, the Programme of Capitalization in Support of Rural Development Policy (PCADR) became involved in the dissemination of three main systems: DMC maize monocropping (a no-till system with conservation of the residues of the previous season), association of maize and rice-bean (a no-till system where maize is intercropped with rice-bean) and a biannual maize–rice-bean rotation (a rotational sequence between maize and rice-bean under a no-till residue management system). Under these three systems, residues from the previous crop are left on the surface of the soil and the following crops are directly seeded into the mulch —either manually, using sticks or hand-jab seeders, or mechanically using small sowing machines imported from Brazil and adapted for hand tractors or medium-sized tractors. Like in conventional systems, the CP888 hybrid maize variety is used. Maize is sown between late April and early May (depending on rainfall distribution and plot location) and harvested between August and September. A local photosensitive variety of red rice-bean is seeded manually (using sticks or hand-jab seeders), either as the main crop in a biannual maize–rice-bean rotation or intercropped with maize. In the first instance, rice-bean is sown in May–June and harvested in

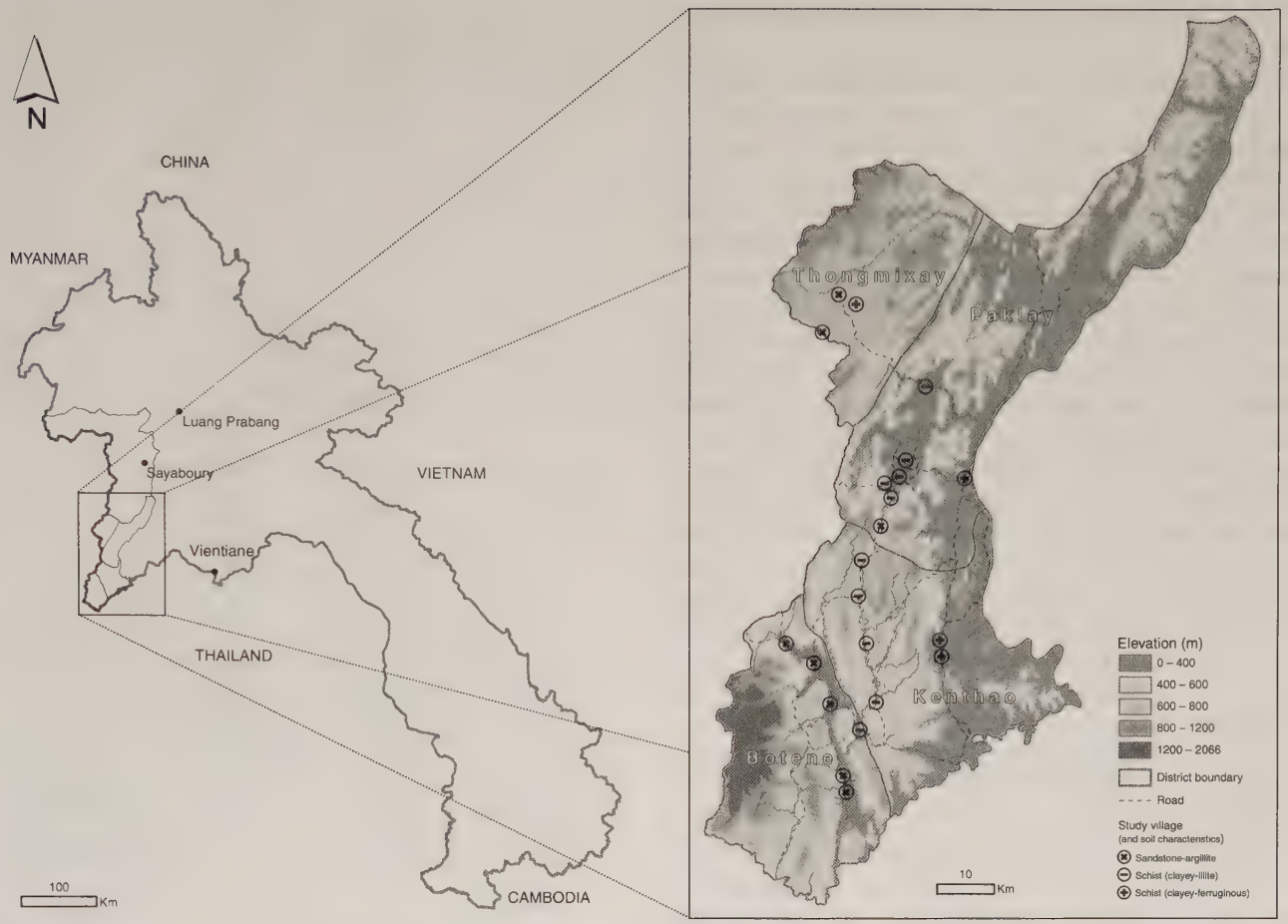

Figure 1. Intervention area of the PCADR–PRONAE projects and villages surveyed.

December. In the second instance, rice-bean is sown 90 days after maize emergence, which allows for good vegetative development at the end of the rainy season, and is harvested in December. In all three systems, weed control involves a pre-sowing application of glyphosate and 2,4-D (dichlorophenoxyacetic acid). In some instances, atrazine is also used to control broadleaf weeds after the emergence of maize. It must be noted that these cropping systems constitute relatively basic forms of DMC. More efficient systems involve diversified rotations and the use of relay crops/cover crops during the winter dry period. Dissemination efforts involved awareness raising and training activities with farmers and extension agents, setting up farmer groups and facilitating the supply of inputs. Between 2005 and 2008, PCADR supported the establishment of farmer groups in 44 villages in the four southern districts of Sayaboury province—involving about 1100 smallholders and 1500 ha of agricultural land.

Survey data

This study used quantitative data derived from two series of questionnaire surveys. A rapid questionnaire survey was conducted annually from 2005 to 2008 to determine several basic farm characteristics (e.g., land tenure, land use, income and farm inputs) in a random sample of 2160 households in 21 target villages (Fig. 1). A more detailed questionnaire survey, including education, wealth and environmental perceptions, was conducted in 2006 and 2008 in 462 households in four villages in Boten, Kenthao and Paklay districts. In addition, during the 2007 cropping season, data on labor requirements, inputs, production costs, crop yield and income were collected in regular interviews with members of PCADR farmer groups—for both DMC maize monoculture and tillage-based maize monoculture plots (121 and 110 plots, respectively). Statistical analysis of these different datasets involved calculation of correlation coefficients between household capital assets, labor, age, education level, rainfed land tenure and the extent of DMC land as a proportion of rainfed land per household. A factor analysis was performed to identify possible relations between the geomorphologic location of the farm and the extent of DMC systems as a proportion of rainfed land per household. The agro-economic data collected on DMC and tillage-based maize monoculture plots were also compared and evaluated statistically.

To obtain more qualitative information, 22 semi-structured interviews were conducted in four villages

selected as representatives of a gradient of environmental constraints. Southern Sayaboury province spans three main geomorphologic zones with different characteristics in terms of slope, risk of erosion and soil productivity: from the west (Thai border) to the east (Mekong river), these zones comprise a steeply sloping and erosion-prone sandstone-argillite area, a productive and moderately sloping clayey-illite schist area with basic rock intrusions, and a productive and relatively steeply sloping clayey-ferruginous schist area (see Fig. 1). Within each village, four categories of farmers were selected for interview: (1) farmers who practiced tillage-based agriculture or shifting cultivation and had never used CA; (2) members of CA farmer groups; (3) farmers who practiced CA but were not members of a farmer group; and (4) farmers who had experimented with CA but had later reverted to tillage-based agriculture. These different categories of farmers were assumed to represent a valuable range of individual positions and opinions about CA.

Results

Diffusion of CA in southern Sayaboury province

In 2008, after four years of dissemination, CA had become a significant component of agricultural landscapes in southern Sayaboury province. However, there were spatial variations in the number of farms practicing CA and in the extent of CA compared to other crop management practices. Boten district had the highest adoption rates with up to 88% in the village of Thanang and 100% in Nongphakbong (Fig. 2). With the exception of Houaylod and Houayped, where 72 and 52% of the farms practiced CA, the villages surveyed in Khentao and Thongmixay districts were comparatively less engaged in CA (11 to 28% of the population). Paklay district ranked last since, apart from the villages of Khonken (17%) and Namgnang (19%), only 1–6% of the farm households practiced CA.

Considering the extent of the main cropping practices in the study area, Boten district again stands out. In the six study villages surveyed, CA had gradually expanded to cover an average of about 40% of the total rainfed area (Fig. 3). This figure is largely explained by the high rates of adoption in Nongphakbong and Thanang villages. In contrast, tillage-based agriculture clearly remained the most popular practice in the other villages surveyed in the district. Although the proportion of CA was lower in Kenthao district, a similar pattern was observed, with high rates of adoption in the villages of Houaylod and Houayped (respectively 30 and 20% of the average rainfed land per household) and dominance of tillage based agriculture in the other villages surveyed. CA was practiced least in Paklay district, where, despite a slight expansion at first, in 2008, CA represented less than 10%

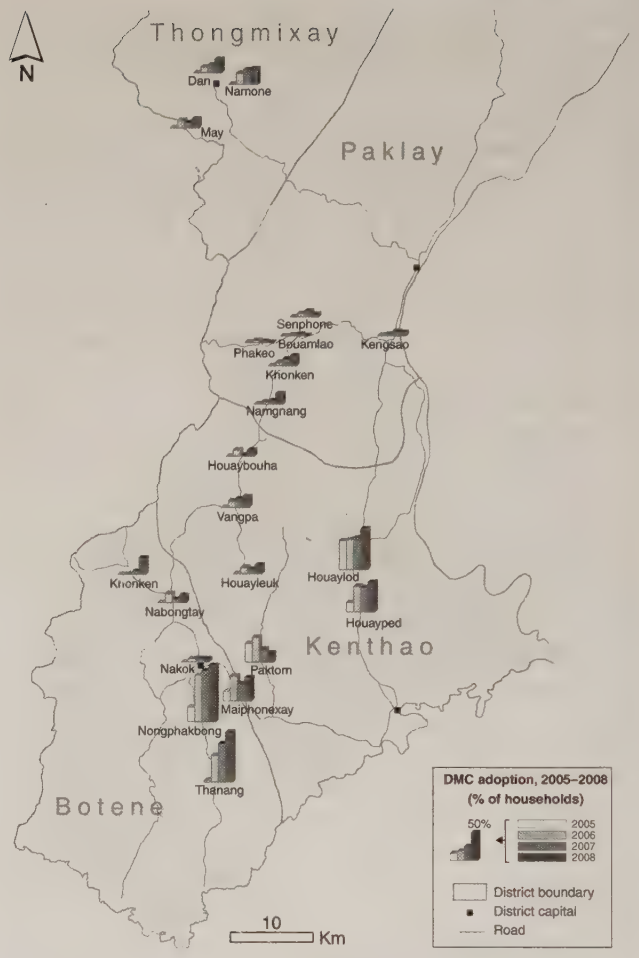

Figure 2. Adoption of CA (% of households, 2005–2008).

of the average rainfed land per household in the six villages surveyed. With a relatively small rainfed area per household, Thongmixay district was quite different from the other districts since in 2008, slash-and-burn remained the main cropping practice in the three villages surveyed. Although CA had gradually increased in the village of Dane (up to 30% of the average rainfed land per household), in the villages of May and Namone, it remained between 15 and 20% of the average rainfed land per household.

The extent of CA in the study area cannot be only attributed to the members of the PCADR and PRONAE farmer groups. As shown by disaggregated data on adoption rates and cultivated area (Table 1), CA spread beyond the farmer groups. In villages such as Paktom neua and Vangpa (Kenthao district), about one-third of the farmers who practiced CA in 2008 had never been members of farmer groups. Kenthao and Thongmixay districts are a good example of 'spontaneous diffusion' since, in the nine villages surveyed, an average of 20–25% of the households practicing CA had never been associated with PCADR and PRONAE. In contrast, the villages surveyed in Paklay district were characterized by very low levels of 'spontaneous diffusion'. Looking at the

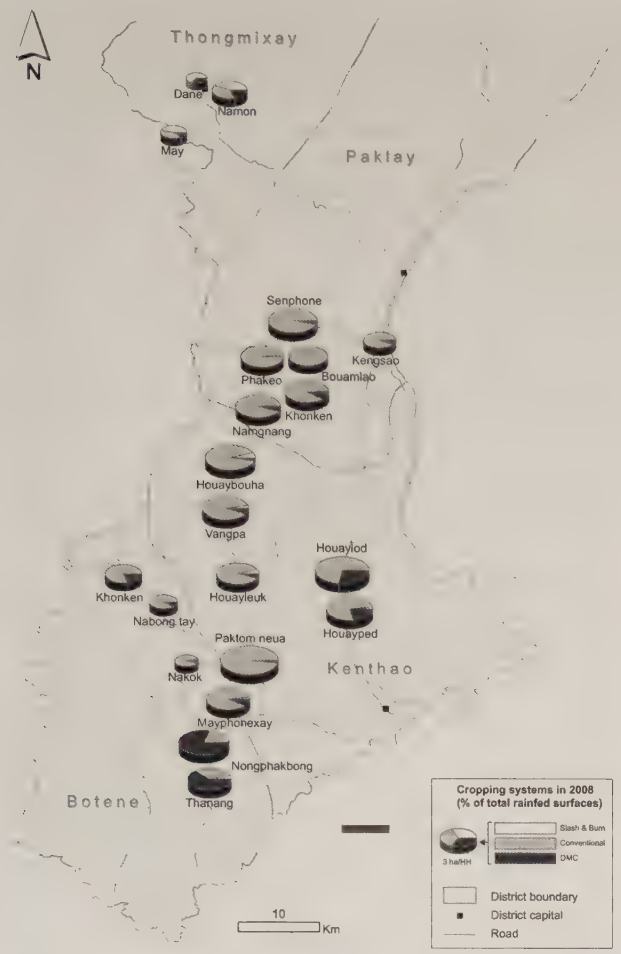

Figure 3. Relative distribution of the main cropping practices in 2008.

total rainfed area under CA (Table 1), the results are similar. Again, Kenthao and Thongmixay districts stand out with 13–16% of the total surface area under CA managed by farming households who had never been members of farmer groups. In contrast, 'spontaneous diffusion' remained quite low in the villages surveyed in Boten and Paklay districts, where 90–100% of the total land under CA was managed by members of farmer groups. At the household scale there were also significant differences in the average area under CA. In the 21 villages surveyed, members of farmer groups practiced CA on an average of 1.9 ha, whereas non-farming households had 1 ha under CA.

Thus, if tillage remained a key agricultural practice in the study area, CA clearly increased in terms of both household engagement and spatial extent during the 2005–2008 period. The case of villages such as Nongphakbong and Thanang in Boten district or Houaylod and Houayped in Kenthao district suggests that, within a few years of dissemination, CA can become a widely accepted and adopted alternative to relatively long-established agricultural practices.

Farm-level determinants for adoption

Statistical analysis. As can be seen in Tables 2 and 3, statistical analysis suggests that labor, wealth, age and education did not play a significant role in determining the level of engagement in CA of an individual household. However, the level of engagement was significantly and positively correlated with rainfed land tenure (although with a very low coefficient). This observation suggests different causal links. On the one hand, it could highlight an *ex ante* linkage between access to land and farmers' willingness to engage in 'experimental' activities. This causal link could be directly related to livelihood vulnerability and risk management strategies. On the other hand, the correlation may also indicate an *ex post* relation between the practice of CA and the potential it represents for farmers to expand their cultivated land. In that sense, the causal link would be more linked to livelihood improvement and supplementation strategies. Comparing rainfed land tenure between adopters during their first year of experimentation and farmers who had never experimented with CA supports the first causal link. As shown in Table 4, rainfed land tenure was systematically higher among adopters. This difference suggests the existence of a land tenure threshold under which farmers are not willing to experiment with CA. Yet, as expected given the rapid agrarian changes observed and the diversity of local situations, this threshold appears to vary quite significantly in both space and time.

Engagement in CA also appears to be influenced by local soil characteristics and productivity. A factor analysis of the relation between geomorphologic location and the relative extent of CA in household rainfed land revealed a very significant correlation between sandstone areas and high levels of engagement in CA (Fig. 4). More generally, factor analysis highlighted a geomorphologic gradient from productive schist areas, with low levels of engagement in CA, to erosion-prone and poorly productive sandstone areas, with high levels of engagement in CA. Again, this correlation may indicate a causal relationship between livelihood vulnerability (to environmental factors in this case) and the adoption of alternatives to tillage as a risk management strategy.

Thus, four observations emerged from statistical analysis: (1) farmers engaged in CA independently of their workforce, wealth, age and education level; (2) farmers who had access to plenty of rainfed land were more inclined to engage in CA; (3) farmers who engaged in CA more easily increased the extent of their cultivated land; and (4) farmers who cultivated soil with limited agricultural potential were more inclined to engage in CA. The following qualitative analysis helped elucidate some of these observations by considering local discourses on socio-environmental constraints and opportunities, and decision-making in relation to CA and tillage-based agriculture.

Table 1. Contribution of farmer groups to the practice of CA (2008).

	Households engaged in CA (%)		Total area under CA (%)	
	Farmer groups (%)	Others (%)	Farmer groups (%)	Others (%)
Boten				
Khonken B	88	12	93	7
Mayphonexay	82	18	92	8
Nabong tay	100	0	100	0
Nakok	83	17	96	4
Nongphakbong	88	13	94	6
Thanang	83	17	90	10
Average	85	16	93	7
Kenthao				
Houaybouha	71	29	76	24
Houayleuk	81	19	88	12
Houaylod	84	16	89	11
Houayped	77	23	81	19
Paktom neua	64	36	81	19
Vangpa	64	36	75	25
Average	77	25	84	16
Paklay				
Bouamlao	100	0	100	0
Kengsao	100	0	100	0
Khonken P	90	10	96	4
Namgnang	83	17	96	4
Phakeo	100	0	100	0
Senphone	100	0	100	0
Average	89	11	97	3
Thongmixay				
Dane	76	24	93	7
May	73	27	86	14
Namon	89	11	82	18
Average	80	20	87	13
Total	80	20	90	10

Table 2. Correlation coefficient matrix (Pearson): Household capital assets, age and education level of the household head and the proportion of DMC in household rainfed land (2006, $n=456$).

	% DMC	Capital assets	Age	Education
% DMC	1	−0.078	0.004	−0.088
Capital assets	−0.078	1	0.047	0.090
Age	0.004	0.047	1	**−0.373**
Education	−0.088	0.090	**−0.373**	1

Underlined values represent significant correlations (at the 0.01 level). Household capital assets were derived from household ownership of transport and agricultural equipment.

Table 3. Correlation coefficient matrix (Pearson): Household labor, rainfed land tenure and proportion of DMC in rainfed land (2008, $n=2032$).

	% DMC	Land tenure	Labor
% DMC	1	**0.072**	0.031
Land tenure	**0.072**	1	**0.182**
Labor	0.031	**0.182**	1

Underlined values represent significant correlations (at the 0.01 level).

Qualitative analysis. A starting point to better understand the observed heterogeneity in adoption rates is to look at the reasons that encouraged farmers to experiment with CA. In this regard, the questionnaire survey highlighted the fact that, apart from simple curiosity and imitation (which represented the main motivations by far), experimentation with CA was significantly motivated by environmental concerns (Fig. 5). As stated by several interviewees, soil erosion, weed invasion and willingness to better manage soil fertility and moisture were key incentives for experimenting with CA. These motivations link back to observations derived from statistical analysis. As would be expected, with soil erosion and fertility issues being key determinants for experimenting with CA, farmers located in areas of steep slopes and erodible soils are likely to feel particularly concerned and hence more

Table 4. Average rainfed land tenure (ha) among households that had experimented with CA (land tenure during the 1st year of experimentation) and households that had never tried CA (2005–2008).

	2005		2006		2007		2008	
	Exp. CA (n=85)	Never (n=1335)	Exp. CA (n=294)	Never (n=1325)	Exp. CA (n=138)	Never (n=1320)	Exp. CA (n=142)	Never (n=1337)
Boten	2.7	1.5	1.9	1.4	2.2	1.5	2.7	1.8
Kenthao	3.1	2.5	3.1	2.5	3.6	3.1	4.0	3.6
Paklay	3.1	2.9	3.0	2.6	3.5	3.0	3.7	3.0
Thongmixay		0.7	1.2	0.8	1.0	0.8	1.5	1.4
Average	3.0	2.4	2.4	2.2	2.9	2.6	3.2	2.8

A Mann–Whitney test revealed a significant difference between the two samples (at the 0.01 level).

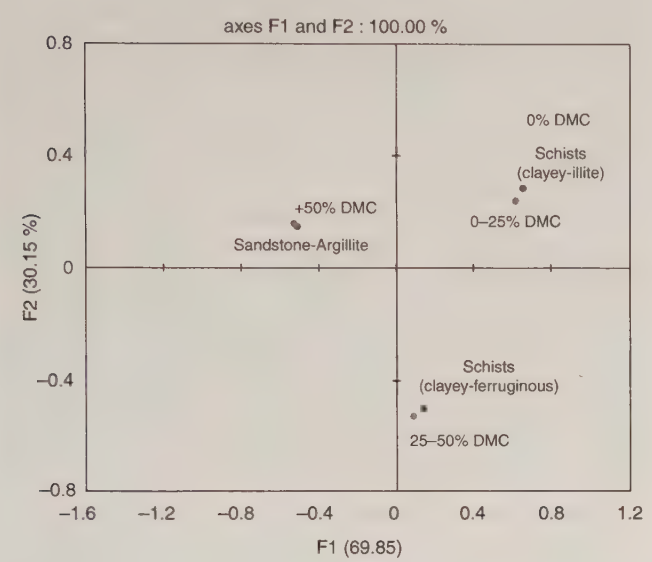

Figure 4. Factor analysis of geomorphologic location and proportion of DMC systems in household rainfed land. Note: The '0% DMC' column—which very significantly outweighs the three other columns—was excluded from the calculation to avoid distortion.

interested in conservation alternatives. This partially explains the very high levels of adoption observed among the farmers in the villages of Nongphakbong and Thanang in Boten district. However, interview data also suggested that environmental concerns and engagement in CA cannot be considered independently from project sensitization activities. Field demonstrations and project meetings figured relatively high among the list of incentives that encouraged farmers to experiment with CA (Fig. 5). As described by several interviewees, project operators can play a significant role not only in promoting solutions to environmental issues experienced locally but also in providing external assessments and in raising environmental awareness:

> '[*What was your initial motivation for experimenting with conservation agriculture?*] I wanted to try the agricultural techniques that the project technicians told us about. They said these systems could increase soil fertility and crop yields.

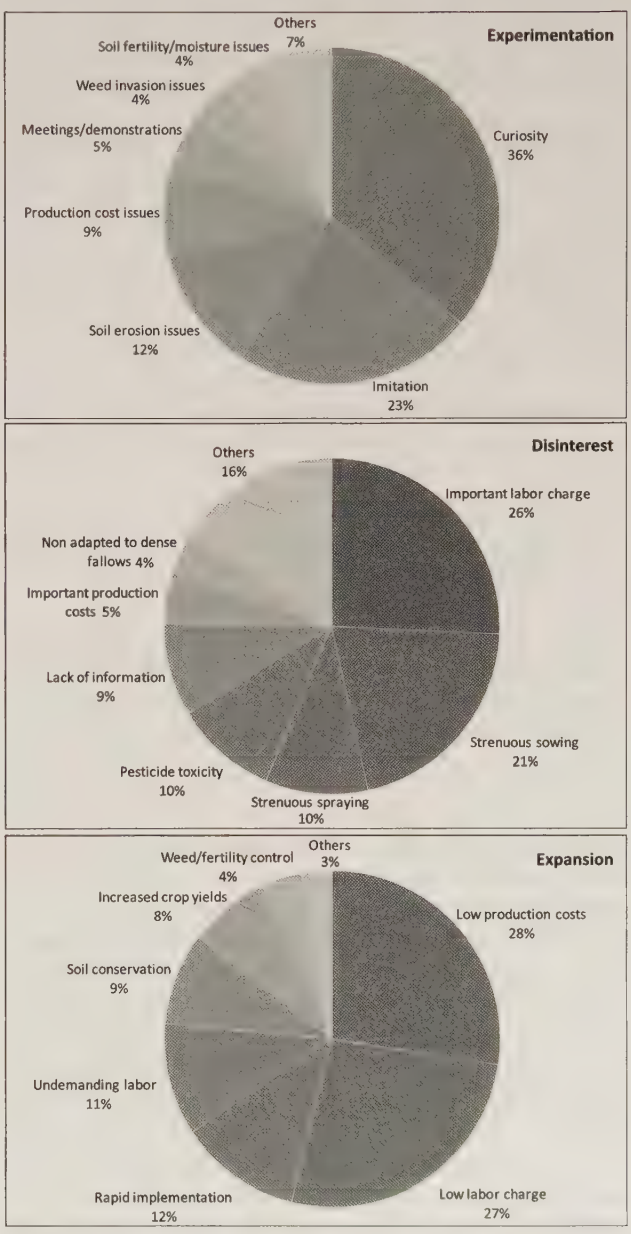

Figure 5. Reasons for trying (232 respondents). not trying (205 respondents) and extending land cultivated with CA (148 respondents) in Nongphakbong, Houaylod, Paktom neua and Bouamlao (frequency of answers, 2008).

Table 5. Agro-economic productivity of DMC maize monocropping and tillage-based maize monocropping systems (2007).

		DMC	Tillage
Boten district	Maize yield (kg/ha)	5237	4729
Seven villages	Production costs (USD/ha)	115	101
29 plots w/DMC	Net income (USD/ha)	633	575
17 plots w/tillage	Labor input (man/day/ha)	37	39
	Labour productivity (USD/day)	19	16
Kenthao district	Maize yield (kg/ha)	4697	4191
11 villages	Production costs (USD/ha)	123	152
46 plots w/DMC	Net income (USD/ha)	548	447
46 plots w/tillage	Labor input (man/day/ha)	41	42
	Labor productivity (USD/day)	15	11
Paklay district	Maize yield (kg/ha)	6242	6392
10 villages	Production costs (USD/ha)	122	188
46 plots w/DMC	Net income (USD/ha)	769	725
47 plots w/tillage	Labor input (man/day/ha)	45	50
	Labor productivity (USD/day)	19	16

A Mann–Whitney test revealed significantly lower production costs for DMC systems (at the 0.01 level).

> My plot is very steep and, during a meeting, they explained how ploughing on steep slopes can cause serious soil erosion and reduce soil fertility. That's why I decided to try the new cropping system.' (Mr Sing, Thanang, June 11, 2009)

In that sense, more than the actual biophysical situation of the farm (e.g., in terms of soil erosion risks and agricultural potential), it was very much the farmer's awareness of environmental threats that played a key role in his adoption of CA.

This observation is in line with the conclusions of Knowler and Bradshaw' review of 31 CA adoption studies worldwide[26]. These authors highlighted the fact that 'awareness of environmental threats' and 'high fertility soils' are often considered as significant determinants for CA adoption (positive for the former and negative for the latter). Similarly, the gradient of CA adoption in our study area, i.e., from productive schist areas to erosion-prone and less productive sandstone areas, appears to have been significantly determined by the different levels of environmental concern between farmers who benefit from highly productive and non-degraded soils and those who have to cope with low productivity and highly erodible soils. However, environmental awareness cannot fully explain the growing importance of CA in villages with relatively good soil conditions.

Willingness to reduce production costs also ranked high among farmers' motivations (Fig. 5). Similarly, farmers' reasons for extending their land under CA were mainly linked to the perceived advantages of the latter in terms of reduced production costs. These perceptions are logical in the context of agrarian transition which characterizes the study area. As mentioned above, farmers in southern Sayaboury province have to cope with increasing farm expenses including for ploughing services, purchase of hybrid seedlings and herbicides. In this context, reduced production costs are likely to be key incentives for the adoption of alternative cropping systems—this time, regardless of the local biophysical context.

In this regard, on-farm monitoring data highlighted non-negligible differences between DMC and tillage-based maize monocropping systems (Table 5). While no statistically significant differences were observed in terms of labor requirements, productivity, crop yield and income, DMC offered clear benefits in terms of reduced production costs (−18% on average). During qualitative interviews, eight out of 13 farmers who had tried CA mentioned excessive production costs associated with tillage as their main reason for testing alternative cropping practices. As argued by the Houayped village chief, the increasing number of people willing to try CA in his village was linked to increasing debt among the farmers who used service providers for tillage:

> '[*How do you see the future of CA in the village?*] I think that more and more farmers will practice DMC. There are about 200 families in the village. Last year, almost 70 of them were members of the farmer group. This year, the group includes 100 families. The farmers who plough their fields can no longer pay back their loans, especially considering the low yields we had last year. Nowadays, everybody wants to try DMC to save money.' (Mr Tchik, Houayped, June 14, 2009)

Again, project sensitization activities appear to have played a critical role in the process. As stated by the majority of adopters interviewed, project meetings and discussions with project officers were essential awareness-raising events and key starting points for experimentation with CA:

> '[*When did you start conservation agriculture?*] I started three or four years ago. [... *What was your initial motivation?*] I went to the project meetings, followed the advice of the technicians and started with two plots of maize. I had a very good harvest that year. This would have been impossible with the conventional system because there was a drought and, in that case, ploughing causes problems of dry soil and ends with low yields. [*What was your motivation for participating to the project activities?*] I wanted to change from conventional agriculture because it is too expensive. You have to pay for everything, for ploughing, for herbicides, for labour ...' (Mr Sinouane, Khonken (Paklay), June 13, 2009)

While low production costs were clearly a major incentive for adoption, some farmers also mentioned a link between

CA and agricultural expansion. For several interviewees, engaging in CA was not only a way of reducing their farm expenses but also meant that some labor could be reallocated to cultivating more land.

> '[*Why did you increase your land under CA?*] I started cultivating larger plots because the cropping system means you can save on labour. You don't need to till your fields by hand and it costs less than ploughing. [... *What do you do with the extra money?*] I can buy furniture for the family. I also paid to extend my paddy fields. [*What do you do with the extra time?*] Before, I used to spend all my time tilling one and a half hectares of land by hand, now I can cultivate four and a half hectares' (Mr Vone, Thanang, June 11, 2009)

This observation sheds a different light on the statistical correlation between rainfed land tenure and engagement in CA. The hypothesis that farmers with more land resources would be more inclined than others to experiment with new practices remains valid and in agreement with the findings of other studies worldwide[26]. However, qualitative data also suggest an *ex post* relation between adoption of CA and agricultural expansion. Thus, although DMC maize monoculture does not present statistically significant benefits in terms of improved labor productivity (see Table 5), some farmers were nevertheless able to cultivate more land without increasing their financial and labor investments.

Frequent references to the experience of neighbors as a reason for experimenting with CA (Fig. 5) suggest that social adherence is an important determinant for adoption. In villages such as Thanang, Nongphakbong, Houayped and Houaylod where CA is practiced by more than half of the villagers and is therefore established as a viable practice, the shift from tillage-based to CA is likely to be easier and perhaps more durable than in villages where CA is still marginal. Similarly, the participation of village leaders in the project may be important. The rapidly increasing adoption rate in Houayped (from 16 to 52% between 2005 and 2008) may partly reflect this point. During an interview, the village chief—who has been an active member of the PCADR farmer group since 2005 and uses DMC techniques on 8 hectares of rainfed land—said he considered village meetings as an opportunity to explain the functioning and benefits of CA to his constituents:

> '[*Do you recommend DMC techniques to the villagers?*] Yes, during village meetings, I often recommend trying DMC systems. I explain how it works, we discuss the cropping techniques, how they differ from conventional agriculture, and their advantages.' (Mr Tchik, Houayped, June 14, 2009)

As described by another interviewee from the same village, the village chief's involvement is not only theoretical since he also gives the villagers practical help in implementing the new techniques:

> '[*What was your initial motivation for experimenting with DMC systems?*] I started DMC because local traders offered loans not only to buy seeds but also for herbicides. So I took out a loan to buy herbicides and then, the village chief came to see one of my plots and explained how to use DMC with maize.' (Mr Heou, Houayped, June 14, 2009)

Generally speaking, the involvement of a village leader in both the promotion of CA and its practical implementation probably helps normalize and/or institutionalize the practice. Subsequent adoption by other farmers is likely to be facilitated. As argued by Swinton[27], social capital embodied in variables like farmers' participation in community organizations can sometimes play a more determining role in facilitating adoption of agricultural innovations than variables such as the biophysical situation of the farm, crop prices, farm assets or even perception of environmental degradation.

So far, our analysis has mainly considered the main possible drivers for adoption. Yet, answers to questions why farmers did not try CA showed that labor requirements, arduous sowing and herbicide spraying were by far the biggest disincentives (Fig. 5). Although labor-related issues may appear unjustified given the agro-economic performance of CA (see Table 5, showing that labor requirements for DMC and tillage-based systems are similar), an observation that was repeatedly made during interviews may provide the explanation: the absence of private operators who supply the technical services specific to CA. Cover crop or residue management, herbicide spraying and sowing in DMC systems require specific equipment and technical know-how. These tasks also require considerable labor investments when large areas are concerned. In a context in which the agricultural sector has mainly been structured around tillage-based maize monoculture, many farmers prefer to use well-established service providers. Even if this system increases farm expenses, the high incomes ensured by cropping maize combined with credit schemes that allow farmers to delay reimbursing their loan until after the sale of their production tend to counterbalance the agro-economic advantages of CA:

> '[*What were your motivations for changing from DMC to ploughing-based agriculture?*] I had to stop last year because I didn't have enough labour to cultivate my plots. I was growing melons in my lowland fields, and that requires a lot of time. [*Did you change for ploughing because DMC requires too much labour?*] No, it does not require a lot of labour, especially if you can use mechanical seeders. Conventional agriculture probably requires more labour but, if you have enough money, you can hire people to work in your fields. With DMC, that is more difficult.' (Mr Phonxay, Paktom, June 12, 2009)

Finally, several factors appear to converge to facilitate or limit the diffusion of complex DMC systems based on crop associations and rotations. In villages such as Thanang and Nongphakbong (Boten district) that are characterized by relatively poor soils but have easy access to markets for secondary crops, crop diversification and

rotations have long been used by farmers as a way to maintain soil productivity. In this context, DMC systems are likely to be considered as just another way of applying long-established intercropping practices. This is not the case in Paklay district where maize monocropping is clearly the norm:

> '[*Which crop do you cultivate in CA?*] I grow maize. I also grow rice and peanuts but with ploughing, not with conservation agriculture. [*Do you plan to associate rice bean with maize at some point?*] No, I think I will only grow maize. We are used to monocropping in this village. Intercropping is impossible here because the villagers don't know how it works. [*Intervention of another interviewee*] Yes, and if we crop rice beans, we have to go to Kenthao to sell the harvest.' (Mr Ma and Mr Bounma, Khonken, June 13, 2009)

Thus, limited agricultural knowledge and limited markets for 'secondary crops' are major constraints for the development of DMC systems based on intercropping and rotations, and hence for the emergence of a genuine CA.

Discussion and Conclusions

The adoption rates and extent of cultivated areas observed in several villages in the study area suggest that, within a few years of research and extension, CA could become a viable and accepted alternative to well-established tillage practices—even in a context of small-scale farming. Thus, this case study provides a counterargument to the conclusion of Giller et al.[14] that CA is generally incompatible with smallholder farming. Statistical evidence suggests that farmers' engagement in CA is not contingent upon farm-level variables such as capital, labor, age and education. Access to land and associated risk-management strategies certainly help shape farmers' decision to try CA. However, the difference in land tenure between experimenters and non-experimenters appears fairly small (0.4 ha on average for the 2005–2008 period) and varies in both space and time. More generally, in line with the assessment of Knowler and Bradshaw[26], the present study indicates that the factors that influence farmers' decision making are highly context specific (e.g., local land degradation and production costs, involvement of local elites, markets for secondary crops). The absence of universal variables explaining local engagement in CA jeopardizes any attempt to extract general theories on farm-level determinants for adoption. However, at the level of policymaking and planning, the case of southern Sayaboury province highlights two important aspects that should be accounted for in any CA dissemination strategy. As indicated by statistical and qualitative evidence, farmers faced with serious agro-ecological constraints and land degradation are more likely to try and to subsequently adopt CA. Thus, environmental sensitization appears to be a key aspect of dissemination. Although dissemination is likely to yield fewer results in areas with productive soils, qualitative data indicate that a dissemination approach emphasizing reduced production costs is also an effective way of encouraging farmers to engage in CA and save money on tillage.

Finally, the question of the integration of CA in the broader agricultural industry also appears to be essential. On the one hand, the dissemination of CA in southern Sayaboury province benefited from a well-developed maize industry, which allows smallholders to obtain a monetary income and thus to cover the costs associated with agricultural intensification. On the other hand, the fact that the agricultural sector is entirely structured around tillage-based maize monoculture imposes considerable limits to the diffusion of CA. Without service providers specialized in CA, there are limited incentives for farmers to change from conventional cropping systems. With limited market opportunities for 'secondary' crops, there are also limited opportunities for the emergence of more ecologically intensive CA systems. The integration of grasses and legumes in diversified rotations and as relay crops during the dry season does not only allow for additional fodder and grain production, it also plays key roles in nutrient recycling, pest management and weed control[28,29]. Yet, in southern Sayaboury province, the realization of these benefits is significantly hindered by an overly specialized agrifood market. Without more diversified market opportunities, CA adoption is likely to concern only poorly efficient monocropping systems, based on residue management and requiring important amounts of chemical inputs for weed and pest control. Thus, beyond research and farm extension, the emergence of a genuine CA may also require a transformation of the agricultural industry itself.

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